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Ventilation is a method of maintaining good Indoor Air Quality (IAQ). Demand controlled ventilation is a new control strategy that potentially improves IAQ while minimizing energy costs. However, there are several unanswered questions concerning the application of DCV. For example, how well do current CO_2 sensors perform? Under what conditions is DCV cost benefical? Where is the sensor placement location that results in the highest IAQ. These questions were answered as part of this research program.

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Enclosure 1

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FINAL PROGRESS REPORT

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AUTHORS
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North Carolina A&T State University

LIST OF APPENDIXES

4-A. STATEMENT OF PROBLEM

Indoor air quality (IAQ) has become an important concern for architects, engineers, and building operators. When trying to control IAQ three strategies are most common, source management, filtration and dilution with outdoor ventilation air. The required flow of outdoor ventilation air is typically determined by applying the Ventilation Rate Procedure of ASHRAE Standard 62-1989, Ventilation For Acceptable Indoor Air Quality. When using this approach outdoor air flow rates are determined based on design occupancy levels and tabulated minimum flow rates per person. For example, for offices a minimum of 20 cfm per person is recommended. Because this procedure relies on design occupancy values, for spaces with variable occupancy this results in overairing and unnecessarily high energy consumption. When this occurs one possible control strategy for reducing energy costs is to vary the intake of outdoor air based on sensed levels of indoor pollutant concentrations. Today many sensor manufacturers have recognized the need for IAQ sensors that can be applied to this control strategy. Carbon dioxide sensors are now commercially available for application to demand controlled ventilation strategies.

When applying CO_2 sensors to demand controlled ventilation there are at least three important issues. First is the question of how well the sensors perform for various conditions. Second, is a concern for sensor placement. Third is the issue of cost/benefit. The objective of this research project was to answer these questions. Specifically, the objectives were:

1) To determine the relative performance of selected samples of commercially available CO_2 sensors for application to Demand Controlled Ventilation.

2) To determine which sensor location, either in-room, return plenum, or common return duct, provides the best overall indoor air quality control.

3) To estimate the differences in energy consumption for Demand Controlled Ventilation when applied to different occupancy densities and schedules, and climatic regions.

These objective were met by applying both experimental procedures in the Indoor Environmental Quality Laboratory at NCA&TSU, and computer simulation techniques.

4-B. SUMMARY OF RESULTS

The results from this research can be summarized as follows:

1) The performance of many of the first group of study CO_2 sensors did not meet manufacturers specifications or the accuracy was such that the sensor was not applicable to demand controlled ventilation. Recent experience suggests that this technology has improved and today's sensors are much more applicable when compared to those from only a few years ago.

2) A normalization procedure was developed to relate the output of a group of study sensors to that of a reference sensor.

3) The sensor located in the return duct resulted in the lowest average pollutant concentrations in the test chambers. The return duct location performed slightly better that the return plenum location and significantly better than the in-room location when large differences in pollutant concentrations existed between the test chambers.

4) Energy reduction for demand controlled ventilation is sensitive to climate, occupancy characteristics, and the HVAC system design and operation, and consequently the investment in DCV should be well informed. The largest energy cost savings are likely when heating loads are high.

4-C. LIST OF PUBLICATIONS

The results from this research have resulted in one completed Masters Thesis, one Masters Thesis being finalized, and five published technical papers. The publications can be summarized as:

MASTERS THESES:

1) Meyers, Darren. "The Development of a Normalization Procedure for Commercially Available Carbon Dioxide Sensors." A Graduate Thesis for The Architectural Engineering Department at North Carolina A&T State University. 1994

2) Bradburn, James. "The Determination of Optimal CO2 Sensor Location for Application to Demand Controlled Ventilation." A Graduate Thesis for The Architectural Engineering Department at North Carolina A&T State University. Pending

TECHNICAL PUBLICATIONS:

1) Meyers, Darren, J. Jones, H. Singh, and P. Rojeski. "An In-Situ Performance Comparison of Commercially Available CO2 Sensors." Proceedings of the 17th World Energy Engineering Congress, Atlanta, GA. December 7-8, 1994.

2) J.Jones, H. Singh, and A. Malik. "Emerging Control Strategies for Minimizing Energy Consumption and Maintaining Acceptable Indoor Air Quality in Industrial Facilities." 4th Industrial Engineering Research Conference, Nashville, TN. 1995.

3) J. Jones, H. Singh, and D. Meyers. "Performance Comparison of Commercially Available CO2 Sensors for Demand Controlled Ventilation." Accepted for publication in the Journal of Architectural Engineering, American Society of Civil Engineers, New York. March, 1997.

4) J. Jones, and H. Singh. "Energy Cost Comparison For Demand Controlled Ventilation Versus 20 CFM Per Person." Proceedings of the 19th World Energy Engineering Congress, Atlanta, GA. November 5-8, 1996.

5) J. Jones, J. Bradburn, and H. Singh. "Effect of Sensor Placement on Indoor Air Quality For Demand Controlled Systems." Proceedings of Clean Air '96. Orlando, Fl. November 19-22, 1996.

Copies of the technical publications are included as part of this report in Appendix A.

4-D. CONTRIBUTING PERSONNEL

The following personnel contributed to the success of this project.

Dr. H. Singh - Principal Investigator
Dr. J. Jones - Research Coordinator

Dr. M. McGinley - Technical Support
Mr. Darren Meyers - Graduate research assistant - received Masters of Architectural Engineering
Mr. James Bradburn - Graduate research assistant - Pending Masters of Architectural Engineering

APPENDIX A

PUBLICATIONS

Chapter 6

An In SITU Performance Comparison of Commercially Available CO_2 Sensors

D.B. Meyers, J. Jones, H. Singh, P. Rojeski

ABSTRACT

This paper describes the preliminary findings of a research program intended to investigate a popular ventilation control strategy known as Demand Controlled Ventilation (DCV). Further scrutiny proved the need for the development of a normalization procedure for commercially available carbon dioxide (CO_2) sensors typically used in buildings operated with DCV.

Twenty-nine (29) CO_2 sensors were calibrated using manufacturer's recommended calibration protocol. Sensor performance was evaluated for steady state and transient conditions in a well-mixed environmental chamber. The background, experimental set-up, analysis, preliminary findings, and implications for DCV applications are discussed.

INTRODUCTION

The widespread concerns for the health, well-being, and productivity of building occupants have been an essential element in maintaining good IAQ at home and in the work-place (1). In most cases, improvements in IAQ are accomplished by increasing the outdoor air (OA) to the building. Although adequate ventilation is not a panacea for insuring good IAQ, inadequate ventilation must be avoided because of the costs incurred due to decreased occupant productivity, occupant health care, and possible litigation (2). Therefore, it is necessary to supply minimum OA ventilation rates to the indoor environment that are consistent with acceptable IAQ while avoiding the energy penalties associated with conditioning large volumes of OA.

With the recent advent of low-cost, accurate CO_2 sensors, and the realization that CO_2 is exhaled by all building occupants at a rate dependent upon occupant density, activity level, and diet, (3) commercial ventilation strategies utilizing CO_2 measurements to comply with the Indoor Air Quality Procedure (IAQP) of ASHRAE Standard 62-1989: *Ventilation for Acceptable Indoor Air Quality* continue to grow.

Unfortunately, there have been few published research results that answer fundamental questions concerning the practical implementation of DCV by the design professional. And even fewer detailed investigations as to the performance of the latest, commercially available CO_2 sensors in DCV environments. Of primary concern to the design professional are the behavior of the sensors which monitor and respond to shifts in the control variable (CO_2). Questions such as:

- Do these sensors respond accurately over a range of CO_2 concentrations?
- What are the transient response characteristics of the sensors?
- Are the sensors susceptible to drift over the life of the building?
- How complicated is the calibration of such a device?
- Can we depend on these sensors to depict the occupancy pattern of the space for DCV applications?

The purpose of this research is to answer some of these questions which are vital to the practical application of DCV.

The research results discussed in this paper are derived from full scale experiments performed in the Indoor

Environmental Quality Laboratory at North Carolina A&T State University, Greensboro, NC. The experiments were performed for a geometrically representative, single occupant office (within the confines of the analysis, a space; 12' (L) x 12' (W) x 8' (H)). An "H-shaped" header was constructed to distribute pure CO_2 to the chamber for tracer tests. Sensors for data acquisition were arranged into a three dimensional matrix. Sensors included thermocouples, omni-directional air flow transducers, and conventional, Non-Dispersive Infrared (NDIR) CO_2 sensors (See FIG. 1). Other chamber space parameters measured were, room dry bulb temperature (dbt), relative humidity (rh), and plenum rh. All efforts were made to maintain the IAQ integrity of the environmental chamber. Perforated, stainless steel, lay-in ceiling tiles were used to minimize off-gassing and facilitate uniformity in the return air (RA) flow.

Twenty-nine (29) CO_2 sensors (including one monitoring OA CO_2 ppm) were calibrated using manufacturer's recommended calibration protocol. Upon the mastery (2 years of in situ observation) of the calibration protocol and signal conditioning for use in a laboratory based data acquisition system (DAQ), sensor performance under steady state and transient observation in a controlled environmental chamber was less than predictable. It was decided to pursue investigations into the normalization of the individual CO_2 sensor outputs. This would facilitate the accurate completion of the projects initial objectives, and allow the research team to better understand the CO_2 sensors response characteristics.

BACKGROUND

DCV is a ventilation control strategy developed to maintain acceptable Indoor Air Quality (IAQ) while minimizing the energy consumption of a building's Heating, Ventilating, and Air Conditioning (HVAC) system. The approach, which modulates the outdoor ventilation air flow supplied to the space by sensing the level of a pollutant (usually CO_2), is best applied in environments with highly variable occupancy patterns (*i.e.* schools, theaters, conference rooms, auditoriums, etc.).

Codes & Standards

There is a growing trend in building codes to require the design professional to follow the American Society for Heating, Refrigerating, and Air-conditioning Engineers, (ASHRAE) Standard 62-1989: *Ventilation for Acceptable Air Quality* for determining ventilation requirements in their facilities (4). The Standard emphasizes the compatibility between energy consumption and acceptable IAQ. The ASHRAE Standard 62-1989 allows two methods for determining the amount of OA ventilation air to bring into the building to maintain acceptable IAQ. Those methods are the Ventilation Rate Procedure (VRP) and the Indoor Air Quality Procedure (IAQP).

The VRP, which is the prescriptive and most used design method, dictates that the designer calculate ventilation requirements for the building based on the maximum level of occupancy and functions within the building. Minimum OA rates are given in ASHRAE 62-1989 in tabular form to achieve acceptable IAQ by controlling CO_2, particulates, and bio-effluents (odors)(5). The prescribed minimum OA ventilation rates never fall below 15 cfm of OA per person.

The VRP may be inappropriate for use in cases of unusual source contaminants, multiple spaces being ventilated by a common system, or highly variable occupancy schedules (2). The IAQP is an alternate compliance method included in ASHRAE 62-1989 which allows the designer to calculate the amount of OA ventilation to be provided based on expected pollutant generation rates in the conditioned space (5-7). It is important to note, however, that the inherent characteristics of the facility must first be identified and limits for any pre-existing contaminants present considered. Thus, where the primary pollutant is from human occupants, CO_2 proves to be the best indicator (5).

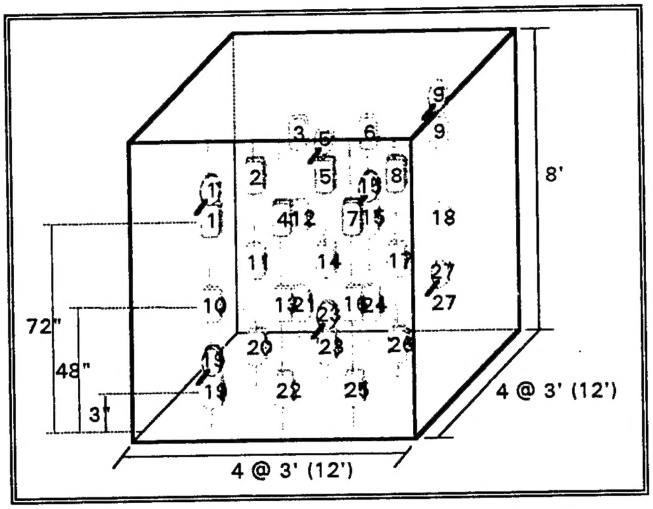

FIG. 1 ENVIRONMENTAL CHAMBER SENSOR LOCATION PLAN

Rectangular **(CO_2 Sensors);** ***Oval*** **(Air Velocity)**

Why Carbon Dioxide?

Because we spend about 90 percent of the day indoors (4), CO_2 is now widely recognized as a surrogate indicator of space pollutant concentrations, occupant density, and odor. (5,8-10,11-20). Throughout the literature concerning the commercial office environment, the primary "pollutant" directly caused by the natural metabolism of humans, CO_2, has been found to correlate well with the perceived quality of the indoor climate. Thus, the concentration (C) of CO_2 in the conditioned space is a good indicator of ventilation demand since it equates well with perceived IAQ, and the occupants are the only relevant source of CO_2: ($C_{outside}$ = 350-400 ppm; C_{breath} by volume ≈ 40,000 ppm) (2). Keeping space CO_2 concentrations to an upper limit of 1000 parts per million (ppm) directly correlates to the VRP's tabular ventilation rates of 15 cfm of OA per person (See FIG. 2) (5).

Utilizing CO_2 as the control variable for determining the quantity of ventilation air in DCV makes use of a CO_2 sensor to modulate the building's multi-position OA damper. Thus, higher levels of CO_2 in the indoor environment will cause a wider opening of the OA damper to ensure adequate ventilation (2). Application of DCV strategies in facilities with variable occupancy patterns could reduce the total amount of OA ventilation air intake for a facility while still maintaining an acceptable building environment for the occupants. Hence, DCV strategies would comply with ASHRAE Standard 62-1989 and result in optimum energy consumption by the facility's Heating, Ventilating, and Air Conditioning (HVAC) equipment. The level of occupancy can be monitored by using CO_2 sensors at locations in the building which best represent the conditioned space CO_2 level. The latest developments in low cost, accurate CO_2 monitors, have increased the ability to comply with the IAQP of ASHRAE 62-1989 using DCV.

Energy studies demonstrate energy savings anywhere from 8 to 50 percent can be achieved depending on the size of the facility and occupancy pattern (12-14,21-23). The greatest promise for energy savings was noted in spaces with highly variant occupancy patterns, or where occupancy patterns were unpredictable (23).

GAS SENSING TECHNOLOGY

Present day gas sensors are broadly classified into two basic types. They are either "interactive" or "non-interactive" in nature (25). Interactive sensors typically allow a sample to come into contact with one or more of the working components of the gas sensor such as electrolytes, sensing surfaces, and electrodes, etc. Examples of such contact are through means of oxidation, absorption, adsorption, etc. Non-interactive sensors do not resemble any of the interactive features. They are basically non-contact (25).

Non-Interactive Sensors

This technology relies on the fact that the atoms of most polyatomic gas molecules vibrate at a certain frequency, called the resonance frequency. This frequency is determined by the mass of the atoms and the strength of their chemical bonds (26). The resonant frequency of each polyatomic molecule is characteristic to those molecules of similar construction (*i.e.* CO, CO_2, CH_4, have strong absorption bands at 4.67, 4.26, and 3.35 microns respectively) (25).

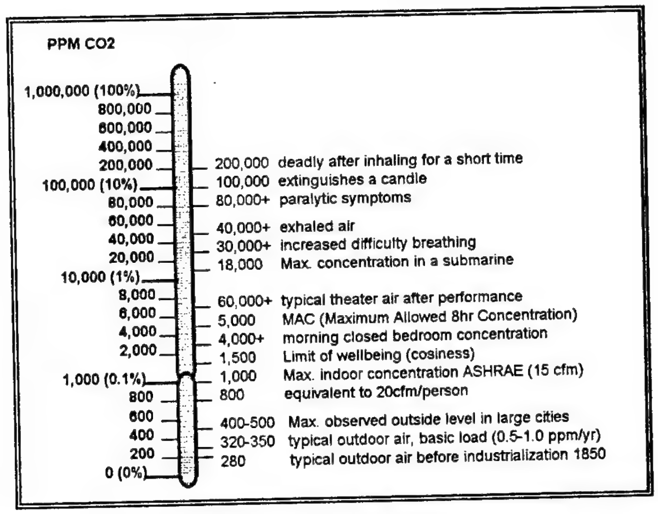

FIG. 2 THE CO_2 THERMOMETER (10,24)

The frequency of IR radiation is of the same order of magnitude as molecular vibrations, approximately 10^{-13} Hz (26). IR radiation can interact with a molecule and transfer energy to it if, and only if, the frequency of the radiation is exactly the same as the resonant frequency of the molecule. When IR radiation is absorbed by a molecule, the molecule gains energy and vibrates more vigorously (26). The amount of light energy absorbed can be observed by measuring either the heat energy released or the associated pressure increase. Both are proportional to the concentration of the absorbing gas molecules (26). One of the strongest attributes of IR gas detection is its ability to detect gases with little or no interference from other gases.

Non-Dispersive Infrared (NDIR) Gas Sensors

There are various arrangements of CO_2 sensors to select from. Several different models of CO_2 sensors were priced, investigated, and evaluated. However, the NDIR

CO_2 sensor's desirable characteristics of low-cost and quick response made it the sensor of choice during the evaluative portion of the study.

A typical NDIR bench for gas measurement includes a high-energy IR source; a motor-driven mechanical chopper for source modulation; a mechanical pump to direct gas through the sample chamber; an optical, thin-film, narrow-bandpass, interference filter for specific wavelength selection, and a sensitive IR detector. It also requires expensive IR optics to focus most of the IR energy from the source to the detector.

The sensor can detect gas concentrations down to ppm levels, and is also very compact. With the exchange of only the optical interference filter, the sensor can detect any one of a large number of gases and chemical vapors that have absorption bands in the IR spectrum. Weight: 12 oz.; height: 7.56"; width: 3.75"; and depth: 3".

EXPERIMENTAL SET UP

Experiments were performed in the Indoor Environmental Quality Laboratory, NCA&TSU, for a geometrically representative, single occupant office, a space; 12' (L) x 12' (W) x 8' (H). The chamber is constructed with exterior aluminum, an exterior vapor barrier, R-11 insulation, an interior vapor barrier, and interior stainless steel. The experiments required altering the environmental chamber and re-configuring the HVAC system (See FIG. 3). A small fan coil unit (approximately 800 CFM) was installed and configured with a fractional, air-cooled chiller (2.1 tons) to provide conditioned or non-conditioned OA to the environmental chamber. A reheating coil was installed to control the temperature of the OA entering the environmental chamber. Physical alterations to the chamber included creating an opening in the ceiling. This opening allowed for the access of supply air (SA) from the AHU and the egress of the exhaust air (EA) from the chamber. There was no allocation for recirculated space air.

A plenum ceiling was installed in the chamber consisting of (17) stainless steel, 2' x 4' lay-in ceiling tiles, each with (72) 3/4" diameter holes. Stainless steel ceiling tiles were chosen to maintain the IAQ integrity of the chamber and minimize offgassing. The matrix of perforations in the ceiling theoretically creates uniformity in the RA flow pattern throughout the chamber.

The three dimensional matrix of (28) NDIR CO_2 sensors (excluding $OACO_2$) and (27) T- type thermocouples were arranged in a cube matrix 9' x 9' x 9'. Three occupant positions were considered when designing the sensor matrix: lying, seated, and standing. These positions (within the levels 3" and 72" above the floor, and 2' from any wall or ventilating device) are representative of the occupied zone as defined by ASHRAE (5). Each sensor was independently powered, and wired to a laboratory DAQ system.

An "H-shaped" dispersion apparatus was constructed to deliver pure CO_2 uniformly to the chamber during tracer testing. The apparatus, with vertical legs spanning 12', horizontal leg of 6', and dispersion jets at 12" OC, was located just below the plenumed ceiling. Mixing in the chamber was accomplished via two oscillating fans. The fans were allowed to run throughout the duration of the test to maintain "well-mixed" conditions.

The DAQ platform for operation of the acquisition software was a Macintosh, Mac Quadra 800 with 8M/500Mb memory and CD ROM capability. The DAQ monitored 29 individual CO_2 sensors, 31 T-type thermocouples, 9 omni-directional hot wire anemometers, and two relative humidity sensors. DAQ has the capabilities to: monitor numerous data channels at adjustable acquisition rates (in sec), monitor and multiplex various sensor types (voltage, t-thermocouples, current, etc.), set channel high / low signal limits, monitor independent reference and real-time channel readings (via analog, digital, graphical, and chart form), incorporate mathematical signal conditioning before test data is written to file, indicate individual data tracks utilizing colors or symbols, and record and save test data to a spreadsheet file with headings.

CALIBRATION PROCEDURES

It is important to understand the three methods of calibration recommended by the manufacturer and practiced throughout the duration of the research: Verification, Single-Point Calibration, and Full-Calibration.

Verification involved the affirmation of a known concentration of CO_2 by supplying the sensor with that known concentration, and "verifying" the result via the sensor's LCD, or DAQ accordingly.

Single-Point Calibration involved the adjustment of the sensor's offset (zero/slope) setting by supplying a known concentration of CO_2 or 0% CO_2 (100% N_2) to the sensor, and adjusting the zero potentiometer accordingly.

Full Calibration involved the adjustment of the sensor's offset (zero) and span settings by supplying a known concentration of 0% CO_2 (100% N_2) to the sensor, and adjusting the zero potentiometer accordingly. Then sup-

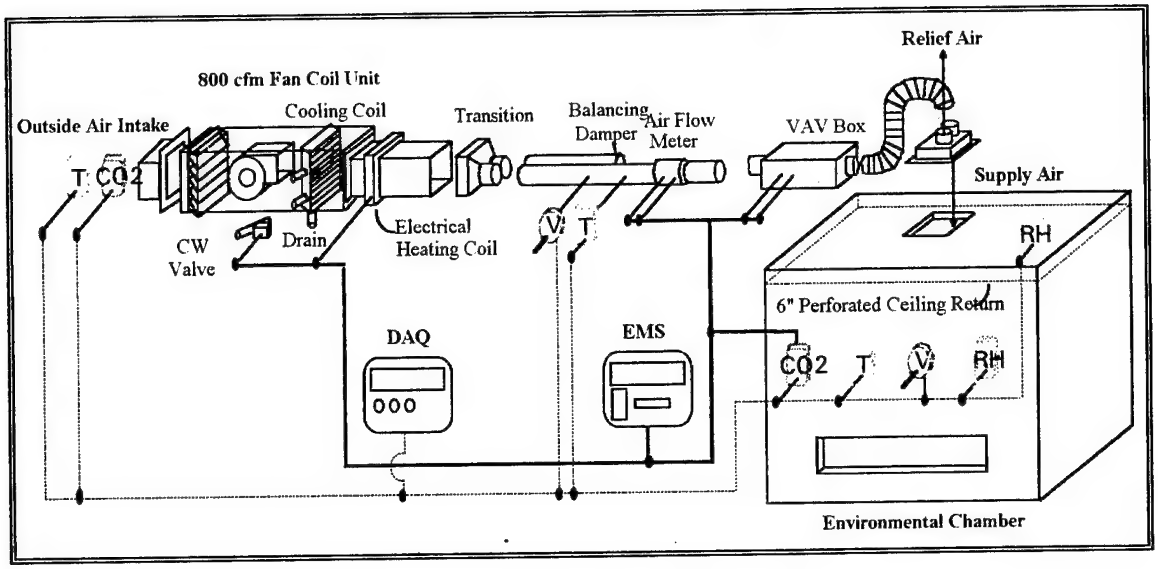

FIG. 3 SCHEMATIC EXPERIMENTAL SET UP

plying a known concentration of 0.2% CO_2 (2000 ppm) span gas to the sensor, and adjusting the span potentiometer accordingly. 2000 ppm is the upper limit of the sensor. Therefore, full calibration intends to linearize the output over the entire range of the sensor

Equipment required for calibration includes: Digital multi-meter with a minimum range of 0-5 Vdc or another means of converting the sensor's signal to a concentration (ppm) output; a small (0.07" or less) flat-blade adjustment screwdriver; calibration gases (preferably 0% CO_2 (100% N_2); 800-1000 ppm CO_2, and 2000 ppm CO_2); calibration adapter blanket, adapter blanket securing clips, regulated gas valving capable of maintaining 15 psig ±2 psig, connector tubing, and a flow meter capable of maintaining flow between 400-800 ml/min.

PRELIMINARY FINDINGS

All 29 sensors were calibrated to manufacturer's specifications. For the sensors in question:

(20) Model A (Aged 1 Year), Wall Mounted, CO_2 Sensors (One of which was utilized in a pitot static duct take-off application), 0-2 Vdc output, 0-2000 ppm, LIN, Accurate to larger of ±5% FS or ±50 ppm, ±100 ppm annual drift.

(4) Model B (Aged 2 Years), Wall Mounted, CO_2 Sensor Controllers, 4-20 mA output, 0-2000 ppm, LIN, Accurate to larger of ±5% FS or ±50 ppm, ±100 ppm annual drift.

(3) Model C (Aged 1 Year), Wall Mounted, CO_2 Sensors, 4-20 mA output, 0-5000 ppm, LIN, Accurate to larger of ±5% FS or ±100 ppm, ±100 ppm annual drift.

(1) Model D (Aged 2 Years), Duct Mounted, CO_2 Sensor, 0-10 Vdc output, 0-2000 ppm, LIN, Accurate to larger of ±5% FS, ±100 ppm annual drift.

(1) Model E (Aged 2 Years), Wall Mounted, CO_2 Sensor, 0-10 Vdc output, 0-2000 ppm, LIN, Accurate to larger of ±5% FS, ±100 ppm annual drift.

Steady State

Upon completion of full calibration procedures, the sensors' steady state readings of CO_2 concentrations in a sealed, well mixed chamber ranged from 210 ppm to 540 ppm CO_2 (See FIG. 4). The results from the use of Ordinary least squares (OLS) linear regression, to reproduce the "best-fit" calibration slopes unique to each sensor also did not agree with the manufacturers claims that the sensor's output performed linearly over the full range of the sensor. Following these initial readings, problem sensors were identified and recalibrated. This resulted in little improvement in the variance between the sensors.

Transient State

A process was developed to assist in the evaluation of the transient characteristics of each sensor. Rate performance curves were created for each sensor by supplying the sensor with a known, zero CO_2 concentration (100% N_2) and then feeding the sensor a "high-span" limit CO_2 concentration. Which in the case of the CO_2 sensors in

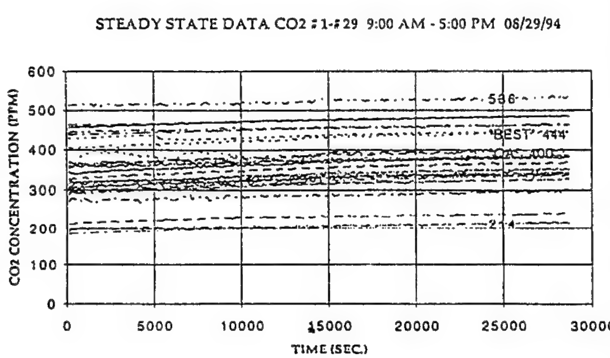

FIG. 4 STEADY STATE DATA AFTER FULL CALIBRATION

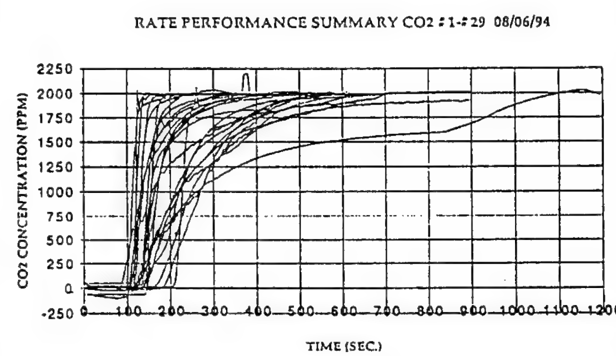

FIG. 5 TRANSIENT DATA AFTER FULL CALIBRATION

question was 2000 ppm CO_2. Thus, a picture of each sensor's response characteristics over its entire range of measurement could be scrutinized. Rate performance curve development took anywhere from 30 to 45 minutes per sensor.

Although the manufacturer's calibration protocol was followed, it can be seen that the time constants for individual sensors ranged from 20 seconds to 6 minutes (See FIG. 5). Sensor response times from a zero CO_2 concentration to a "high-span" CO_2 concentration (2000 ppm) varied anywhere from 50 seconds to 12.5 minutes. It was also noted that response times varied between similar models.

Choice of "Best" Sensor

Following the preliminary findings, which suggested the need for a normalization procedure, a "reference" sensor was needed. The "best" was chosen as that sensor which was most accurate over the entire range of CO_2 and quickest to respond. A compulsory verification of the manufacturer's claim that the sensor's output is linear over the full range of the sensor was performed. This was done in conjunction with rate performance curve development. Thus, in addition to the zero and "high-span" limit CO_2 shocks fed to the sensors during rate performance development, a known "mid-span" limit CO_2 concentration was fed to the sensors and recorded. OLS linear regression was utilized to develop the equation for a line of best fit. This was then compared to the manufacturers recommended instrument equation.

Subjective evaluation of the rate performance data and the regressive calibration slope data was accomplished. The optimal sensor would have a relatively quick response time to a change in CO_2 concentration (ΔC_n) of ($\leq$ 2 min), preferably quicker, and perform the best with respect to comparison of linearity and accuracy of the subject sensor's output equation to the manufacturers internal instrument equation.

Statistical analysis of the steady state and transient conditions was then performed. The "best" sensor was chosen from the sample of sensors near the statistical mean of the steady state data from all sensors, and which complied with the subjective qualifications stated above (See TABLE 1).

TABLE 1. "BEST" SENSOR (MODEL A)

Instrument Slope ppm = 1000 V + 0	Laboratory Slope ppm = 1013.6 V - 33.6	
Response Time: 150 sec.		
Test CO2 (ppm)	**Avg. Voltage (V)**	**Indicated CO2 (ppm)**
0	0.0293	-2.97
810	0.8363	815.03
2000	2.0033	1997.94

Performance Patterns

A CO_2 tracer test was performed for four CO_2 seeding concentrations (2000, 1500, 1000, 500 ppm) in the

environmental chamber, and observed over an 8 hour period. Pure CO_2 was delivered to the 1152 ft³ (12' x 12' x 8') chamber at 10 psig for 00:02.00, 00:01.30, 00:01.00, and 00:00.30 (120, 90, 60, and 30 sec.) to obtain "well-mixed," average initial CO_2 seeding concentrations of 1996.14, 1521.49, 1036.09, and 495.76 ppm respectively. Average OA CO_2 concentration throughout the duration of the testing was recorded. Mixing in the chamber was accomplished via two oscillating fans. The fans were allowed to run throughout the duration of the test to maintain "well-mixed" conditions. Minor variance of the temperature measurements in the environmental chamber verified the "well-mixed" condition.

Steady state data was plotted with the difference between the reference sensor reading and the study sensor (Y_R - Y) in ppm as the ordinate and the study sensor reading (Y) in ppm as the abscissa (See FIG. 6). Upon subjective evaluation of ΔY vs. Y from the preliminary data, 4 distinct patterns emerged. These are shown in Figure 6. Out of the 29 sensors, 26 were involved in the steady state evaluation. The remaining three were the reference, "best" sensor; the OA CO_2 sensor, and one sensor which was out for repair.

Pattern I was linear. With sensors having this characteristic (6 out of 26), ΔY was largest during the 2000 ppm CO_2 seeding, and smallest during the 500 ppm CO_2 seeding. All, 6 out of 6, of the sensors with this characteristic became more accurate as CO_2 concentration decreased.

Pattern II formed a check-mark shape declining down and to the left. With sensors having this characteristic (12 out of 26), ΔY was largest during the 2000 and 1500 ppm CO_2 seedings, and smallest during the 1000 ppm CO_2 seeding. 8 out of 12 sensors with this characteristic "bottomed out", or became more accurate, as the chamber conditions grew nearer to 1000 ppm CO_2 ±100 ppm. 3 out of 12 sensors with this characteristic became more accurate, as the chamber conditions grew nearer to 500 ppm CO_2 ±100 ppm. Most, 10 out of 12, of the sensors with this characteristic were closer to the reference sensor during chamber conditions below 1500 ppm CO_2 ±100 ppm.

Pattern III formed a reversed check-mark shape declining down and to the right. With sensors having this characteristic (3 out of 26), ΔY was largest during the 500 and 1000 ppm CO_2 seedings, and smallest during the 1500 and 2000 ppm CO_2 seedings. Two out of three sensors with this characteristic "bottomed out", or became more accurate, as the chamber conditions grew nearer to 1500 ppm CO_2 ±100 ppm. One out of three sensors with this characteristic became more accurate, as the chamber conditions grew nearer to 2000 ppm CO_2 ±100 ppm. All, three out of three, sensors with this characteristic were closer to the reference sensor during chamber conditions above 1500 ppm CO_2 ±100 ppm.

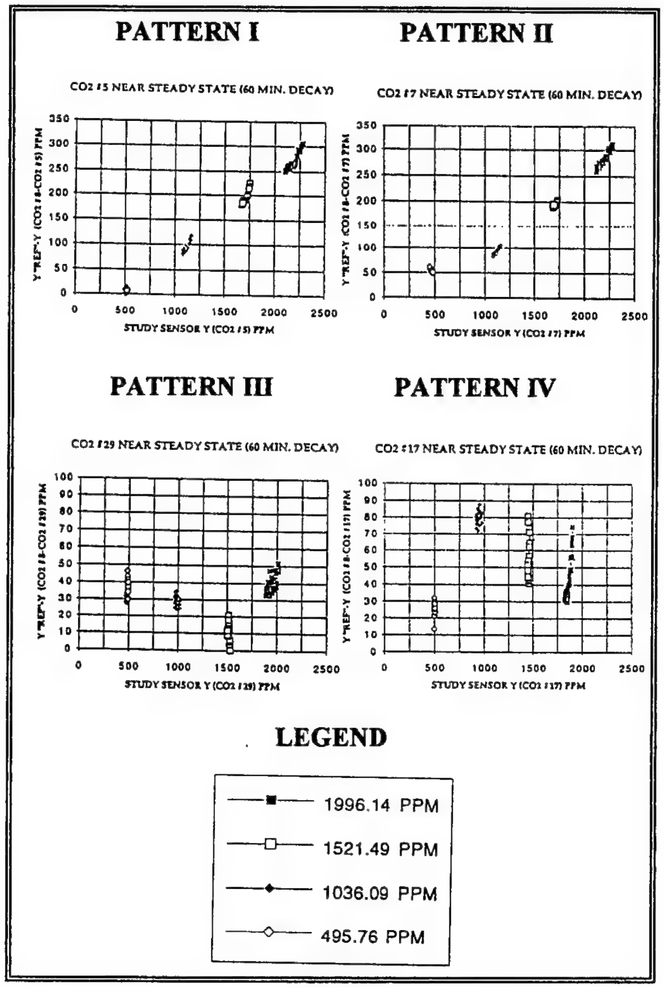

FIG. 6 PATTERNS I-IV STEADY STATE SENSOR DEVIATIONS (ΔY) FOR NORMALIZATION TO REFERENCE SENSOR PPM (Y_R)

Pattern IV formed a upside-down "U" shape. With sensors having this characteristic (3 out of 26), ΔY was largest during the 1000 ppm CO_2 seeding, and smallest during the 500 and 2000 ppm CO_2 seedings. All, three out of three, sensors with this characteristic were least accurate between 800 and 1200 ppm CO_2 ±100 ppm. Yet, each sensor was closer to the reference sensor during

chamber conditions below 500 ppm CO_2 ± 100 ppm and above 1500 ppm CO_2 ± 100 ppm.

IMPLICATIONS FOR SYSTEM CONTROL

This new information deals with the breakdown of the output of a very popular, commercially available CO_2 sensor. The sensor output is typically used as a surrogate monitor of OA ventilation and interrelated IAQ issues. Building operators should, at least, recognize the potential implications of the performance differences shown in this paper.

For instance, during the application of these sensors in a multizone environment utilizing discriminator control to vary OA ventilation levels, the inherent intractability of the sensors, themselves, could have severe implications on air conditioning and air transport energy costs. For example, if one sensor in the multizone matrix is an outlier (High or Low), ventilation demand could be affected accordingly throughout a significant portion of the facility.

The interaction between occupant activity and ventilation demand, expected of a DCV strategy could be significantly unpredictable. As if existing interactions between the components of a control function (*i.e.* sensor, VAV box, actuators, energy management system (EMS)) are not retarded enough; an outlying sensor could perpetuate this condition to the point where ventilation dependent on a surrogate measure of occupancy is no longer appropriate.

Building operators could utilize this information to adapt their facility's EMS to compensate for the sensor's lag and/or lead time until a comfortable solution is achieved. Convincing effects with regard to the facility's OA ventilation demand, energy use, and occupant comfort/productivity could be attained. The ramifications of success significantly affect professionals in the building and design community who currently employ or plan to apply control strategies utilizing this popular CO_2 sensor.

FUTURE INVESTIGATION

Of utmost importance to the creation of a uniform operational strategy for the 29 separate CO_2 sensors is that they perform predictably during steady state conditions. But, it is equally important that the sensors perform similarly during transient conditions. Transient meaning time response to a higher or lower CO_2 (ppm) shock. A normalization procedure for commercially available CO_2 sensors should consider 1) near steady state adjustments, 2) transient adjustments.

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Emerging Control Strategies For Minimizing Energy Consumption and Maintaining Acceptable Indoor Air Quality in Industrial Facilities

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ABSTRACT

The widespread concerns for the health, well-being, and productivity of building occupants have led to the re-evaluation of codes and standards aimed at maintaining acceptable Indoor Air Quality (IAQ). The Occupational Safety and Health Administration, for example, is currently considering revising its regulations concerning IAQ in the workplace. In 1989 the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) revised its Standard 62, Ventilation For Acceptable Indoor Air Quality, raising the minimum acceptable outdoor air flow rate from 5 to 15 cfm per person. The revision of these standards could have serious consequences for energy consumption.

For the heating, ventilating, and air conditioning system (HVAC) designer two strategies are most common for controlling airborne pollutants, filtration and dilution. Each of these has potential consequences for energy consumption. Filtration, for example, may require more motor power to overcome the larger pressure drop across the filter. Dilution typically is accomplishedby increasing the outdoor air ventilation flow rate. Since this air must be heated or cooled, increasing the flow rate will increase energy consumption. The challenge for the HVAC engineer is to find operating and control strategies that maximize the benefit/cost of both filtration and dilution.

When coupled with Variable Air Volume (VAV) systems, achieving the maximum benefit/cost from both filtration and dilution can be complicated. For example, ASHRAE Standard 62-89 allows two procedures for maintaining acceptable IAQ. The Indoor Air Quality procedure allows the ventilation flow rate to vary in response to changes in the indoor pollutant concentrations. Varying the room supply air flow rate based on thermal and IAQ variables presents a new challenge to the system designer.

With the widespread use of microprocessor based controls for building systems, the opportunities are great for controlling the HVAC system while simultaneously considering thermal and IAQ conditions. This paper describes emerging HVAC system design and control strategies that seek to maintain acceptable indoor air quality while minimizing energy costs.

INTRODUCTION

The increased public awareness for the potential health effects of poor indoor air quality, and the concern for litigation of building owners and system designers has led to revisions to many codes and

standards related to indoor air quality. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, for example, is currently revising its Standard 62 - Ventilation For Acceptable Indoor Air Quality. The Environmental Protection Agency and the Occupational Safety and Health Administration are considering more stringent guidelines and regulations associated with indoor air quality in the workplace. These changes are likely to have pronounced consequences for building owners and operators, employers, and HVAC system designers.

While concern for indoor air quality has been increasing, energy conservation continues to be a point of interest. The challenge is to develop building operation and system control strategies that maintain acceptable indoor air quality while minimizing energy consumption. However, care must be taken to balance these two concerns. For example, annual energy consumption for buildings in the United States typically range from between \$1.00 and \$3.00 per square foot per year, while the cost of an employee's wages and salary might be \$100 to \$200 per square foot per year. Obviously, a reduction in energy costs at the expense of reduced employee productivity is not cost effective.

Computer based controls such as Direct Digital Controls (DDC) and emerging sensor technologies such carbon dioxide or volatile organic compounds (VOC) sensors present many opportunities to simultaneously consider energy conservation and indoor air quality. This paper discusses emerging HVAC system control strategies that considers both of these issues.

IAQ ISSUES

There are many pollutant sources in industrial facilities. Solvents for cleaning floors or machinery, raw materials for production, occupant body odor and perfumes or colognes, offgassing of building materials, paint, and combustion engine exhaust are only a few sources commonly found. These sources can be characterized as either transient or continuous. Transient sources are only intermittently present. These might include paint and cleaning solvents that are only occasionally used. Continuous sources are always present and emit at a nearly constant rate. Examples of continuous sources might include offgassing of building materials and emission from raw materials of production. Continuous sources are typically easier to identify, quantify, and control, either through local exhaust or increased ventilation. Transient sources, on the other hand, typically cannot be easily identified, quantified or controlled. The variability of these sources for both duration and concentration, creates challenging short term control problems. However, since these pollutant sources are short term, they also represent the greatest opportunities for IAQ control and energy conservation.

When controlling pollutants three strategies are most common, these include: source management, filtration, and dilution (Giles). Source management might involve proper storage of cleaning materials or local exhaust. Filtration includes either central or local removal of pollutants by passing the room air through a filtering device. Filtration typically involves either particulate or gas-phase contaminant removal. Pollutant dilution is commonly accomplished by providing outdoor air to the room. Both filtration and dilution are strategies that should be considered during the design and operation of the heating, ventilating, and air conditioning system.

DEMAND CONTROL STRATEGIES

For transient pollutant sources, control strategies that respond to variances in concentration are most desirable. In this way, only the filtration or dilution needed

to control the problem is used, reducing waste when compared to a control approach where HVAC system designs and operating parameters are established for a "worst case" condition. Strategies that allow control action to be taken in response to variations in pollutant concentrations are commonly termed Demand Control Strategies.

ASHRAE Standard 62-1989 allows two procedures for maintaining acceptable IAQ; The Ventilation Rate Procedure and the Indoor Air Quality Procedure. The Ventilation Rate Procedure (VRP) is the prescriptive and most commonly used method. For the VRP the volumetric flow of outdoor air supplied to the space is determined from tabulated values for the given characteristics of the space. For the VRP the design conditions are typically established for "worst case" conditions which results in overairing and energy waste. The Indoor Air Quality Procedure, on the other hand, allows the ventilation flow rate to vary in response to changes in the indoor pollutant concentrations. The IAQ procedure presents opportunities to simultaneously control indoor air quality while minimizing energy consumption. With the increased use of microprocessor based controls and the increased availability of IAQ sensors, simultaneous control of IAQ and the thermal environment are easily accomplished.

HVAC SYSTEM SOLUTIONS

While there are many possible combinations of HVAC system type and control options capable of simultaneous control of thermal and IAQ conditions, four conditions will be discussed in detail. These include:

1) Constant Air Volume with Demand Controlled Ventilation.
2) Ventilation control for a Variable Air Volume system.
3) Ventilation control for a Double Duct VAV system.
4) Filtration by-pass control for a constant volume system.

Constant Air Volume with Demand Controlled Ventilation

Many existing buildings are heated and cooled with constant air volume systems. For these systems, the position of the outdoor air dampers can be modulated by a controller based on the input from a pollutant sensor. **Figure 1** shows a multizone air handling unit with simultaneous control of IAQ and the zone temperature. The position of the hot and cold deck dampers are set based on the value of the zone thermostat. This proportional control action is typical of multizone systems. The IAQ control includes a pollutant sensor (possibly carbon dioxide) located in the zone. The outdoor air dampers modulate based on the value of the sensed pollutant. Therefore as the pollutant levels increase, the OA dampers open to provide more fresh air to the zone. For multizone systems with pollutant sensors located in each zone, a comparator controller would be used. For this the OA damper position would be established based on the zone with the greatest demand (largest pollutant concentration). For this control strategy the energy required to heat or cool the outdoor air is minimized because only the minimum OA flow is used to maintain acceptable indoor air quality.

Considerations

There are many considerations when applying a demand controlled ventilation strategy to a constant air volume system. Some of the most important should include:

Cost

For demand controlled ventilation, the additional cost of the sensors and controls could be prohibitive. In an effort to

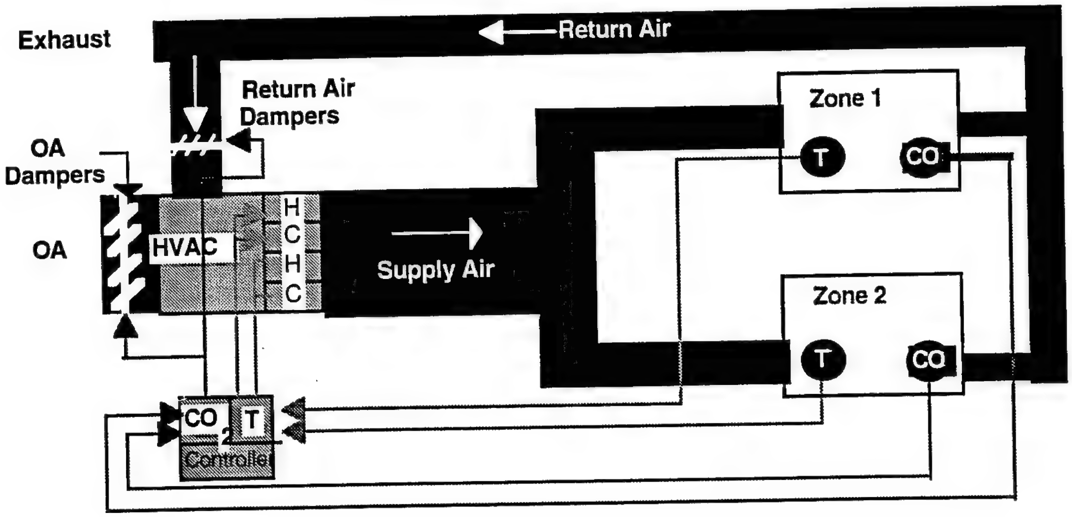

Figure 1. Schematic Multizone System With Demand Controlled Ventilation

control cost, only the minimum number of sensors should be used. This may require careful consideration of the sensor location. Locating a sensor in a common return plenum or duct may or may not provide adequate control of individual rooms. Selecting a representative room or location within the zone to place a single sensor, again may or may not adequately control pollutant levels throughout the entire zone. Consequently the number and location of the pollutant sensors need careful consideration.

Maintenance

Most sensor manufacturers suggest annual re-calibration. This would include not only the cost of calibration but the cost of having maintenance personnel remove and reinstall the sensor. If many sensors are used this could be a large expenditure.

Sensor Performance

All sensors have specifications for accuracy and repeatability. Care must betaken to insure that the accuracy of the sensor is appropriate for the application. For example most commercially available carbon dioxide sensors are accurate to 100 ppm. Recent work by Meyers has shown that for a given sample of CO2 sensors, all from the same manufacturer, the variance of readings can be as much as 100 percent of the mean value (Meyers). If the zone carbon dioxide level is being controlled between 500 and 1000 ppm, the range of accuracy for the sensor would correspond to 20 percent of the control range. If control decisions are being made based on many sensors with this inaccuracy, energy savings may not be as large as expected.

Single Duct VAV With Simultaneous Thermal And IAQ Control

Variable air volume systems have become the most common HVAC system type. This is, in part, because of their energy savings potential when compared to constant air volume systems. Two possible problems with VAV systems is that under part load conditions and low air flow, the required ventilation rates may not be

maintained and room ventilation effectiveness can be reduced. A demand controlled ventilation strategy can help solve both of these problems. Unfortunately, for the typical single duct VAV system, the simultaneous control of the thermal and IAQ parameters is challenging. **Figure 2** shows a schematic of a single duct, variable air volume system with simultaneous control of the thermal and IAQ environments.

Control.

As shown the control of this system requires two levels; a local controller for each zone and a central controller for modulating the fan speed, outdoor air damper position and possibly the cooling coil discharge air temperature. The local controller has two inputs, temperature and pollutant concentration, and two outputs, air flow rate through the zone VAV box and valve position for the reheat coil. The local control sequence would first determine the air flow through the VAV box based on a comparison of setpoint offsets for both the thermostat and the pollutant sensor (comparator control). The air flow rate is based on the greatest demand, either thermal or IAQ. If the air flow rate is based on an IAQ demand and the zone temperature is below its setpoint then the local controller opens the valve on the reheat coil. The valve position is proportional to the offset for the room temperature.

The central controller inputs include the temperatures and pollutant concentrations in all zones as well as the static pressure in the supply duct. Outputs include the outside and return air damper positions, the fan speed, and optionally, the discharge air temperature of the cooling coil. The outdoor and return air dampers are opposed acting and are positioned based on the greatest demand. The demand is determined by comparing the pollutant sensor offsets for each zone and selecting the zone with the largest offset. The fan speed control remains the same as a typical VAV system. To reduce the need for reheat the cooling coil discharge air temperature can be reset based on the cooling demand and largest zone temperature offset for the served zones.

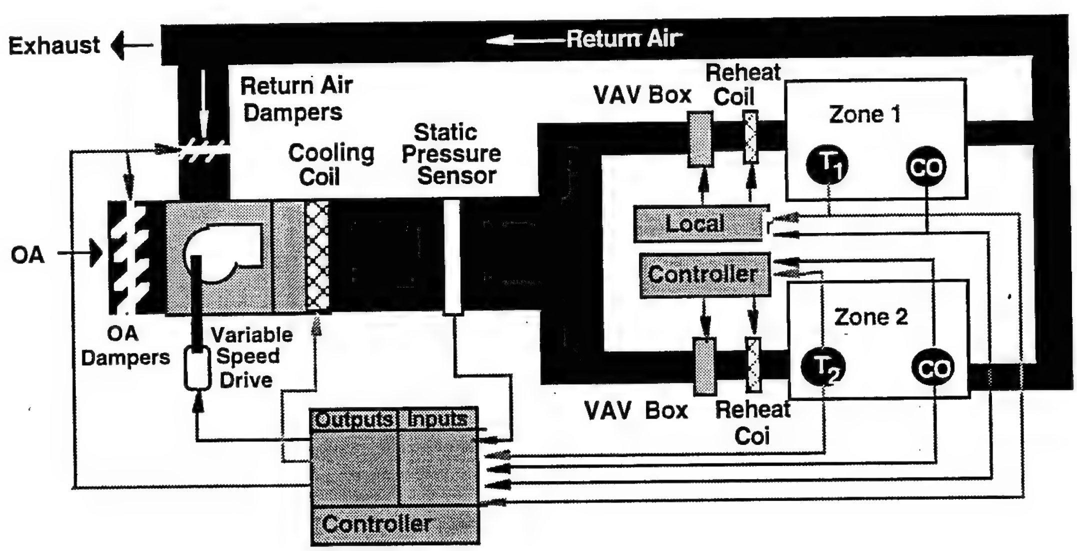

Figure 2. Single Duct VAV System With Simultaneous Thermal and IAQ

Considerations

The single duct VAV system with simultaneous thermal and IAQ control has certain advantages and disadvantages.

Cost

Due to the need for pollutant sensors, local and central controllers, and extensive wiring, the cost of this system can be large when compared to other solutions.

Maintenance

Similar to the constant air volume solution, the sensors must be well maintained if this system is to operate properly. Yearly re-calibration can be expensive. Also, the control sequence for this solution is relatively complex. A solution such as this would likely require a HVAC service person that is knowledgeable in control hardware and software. A person with these abilities is likely to command a higher wage than a lower level technician.

Sensor Performance

Again similar to the constant air volume solution, if control decisions are made based on multiple inputs, care must be taken to insure that the accuracy of the sensors is acceptable. If a wide accuracy range is used control decisions may be unreliable and energy savings can be less that expected.

Double Duct VAV with Thermal and IAQ Control

The third HVAC system solution is a double duct variable air volume system with simultaneous thermal and IAQ control. A schematic of the system is shown in **Figure 3**. The system is essentially two systems. The first is a variable air volume system that serves only the thermal loads. This system operates as a typical VAV system except that for other than during the economizer operation it is 100 percent recirculating. The second system is also variable air volume, but only serves the ventilation requirement. It operates as a typical

VAV system except that the controlled variable is zone pollutant concentration rather than temperature. For both systems the air flow to the zone is proportional to the offset of the sensor, either thermostat or pollutant.

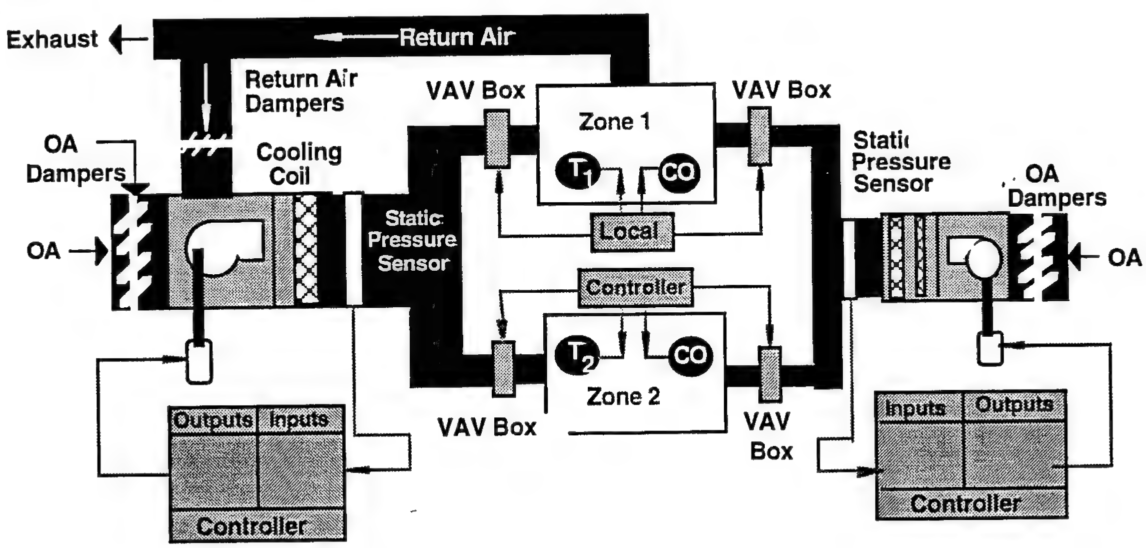

Figure 3. Double Duct VAV System With Thermal and IAQ Control.

Considerations

When compared to other possible solutions this solution has several considerations.

Cost

An obvious disadvantage for this solution is the cost. Rather than having one system, now two systems are used to serve the same space. Similar to the single duct VAV solution, a local controller is needed as well as two central controllers, one for each primary system; this can also increase first cost. The cost of sensors is comparable to the previously discussed solutions.

Maintenance Costs

There are at least two important aspect to consider for maintenance costs. First, since there are two fan systems, there will be an increased need for servicing and maintenance when compared to a single fan solution. Second, the control sequence for this solution resembles that of a typical VAV system and is less complicated than the single duct solution. As a result, controls maintenance should be easier and less costly.

Sensor Performance

As with the previously discussed system solutions the inaccuracy of the sensors and the potential consequences for improper control action should be recognized.

Filtration By-Pass Control

The last HVAC solution for controlling transient pollutants is a filtration by-pass system. An important consideration when using a high efficiency filter is the additional pressure drop across the filter. Because of this pressure drop either lower air flow will be supplied to the space or more fan power is needed to maintain the desired flow rate. If the system is designed to operate with continuous supply air flow through a high efficiency filter, energy is wasted. For transient pollutant sources continuous filtration is not necessary. Therefore a system with filtration by-pass, where supply air is passed through the filter only when pollutant concentrations are above a setpoint, is a possible solution. A filtration by-pass system is shown schematically in Figure 4. For this system the position of the supply air and by-pass

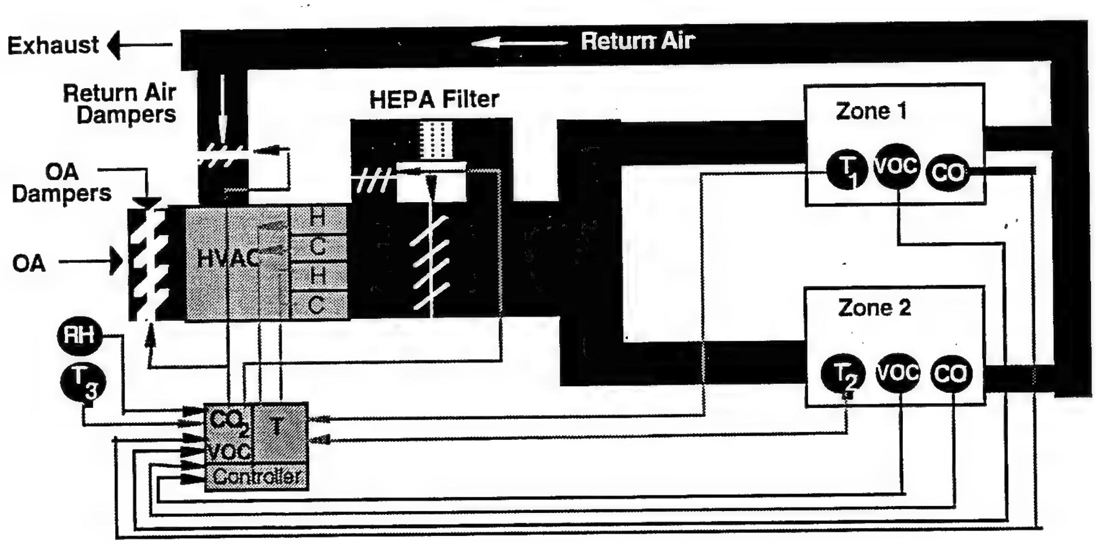

Figure 4. Filter By-Pass IAQ Control.

dampers are set based on the maximum zone pollutant concentration. A comparator selects the zone with the greatest offset. If the pollutant concentration in this zone is greater than an established limit then the by-pass is opened, otherwise the supply air flow does not pass through the filter.

A more complex variation of this control scheme is to simultaneously compare the cost of circulating air through the filter by-pass versus using 100 percent outdoor air. Similar to economizer control, if the outdoor air conditions are such that it is more economical to use 100 percent outdoor air and no filter by-pass, than minimum outdoor air with filter by-pass, then the control action should respond accordingly. By sensing the outdoor air conditions and estimating the cost for conditioning this air, then comparing this cost with the cost associated with the additional fan energy needed to overcome the pressure drop through the by-pass filter, the most economical operation can be achieved.

Considerations

As with the other systems there are many considerations associated with this solution.

Cost

There are at least four cost related considerations for this system. First, as with the other solutions, sensors will be needed to monitor pollutant levels throughout the building. These sensors can be expensive. Second, the cost of the filters and additional ductwork can increase the first cost for the system. Third, the by-pass will require additional space in the mechanical room. Since the cost of providing additional space is typically large, this can create limitations for the application of this strategy. Finally, the cost of the controls and hardware installation must be considered.

Maintenance

As with the other solutions the maintenance and annual re calibration of the sensors can be expensive. The cost of replacing the filter must also be considered. The frequency of filter changes will depend on the filter and pollutant characteristics as well as the operating characteristics of the HVAC system.

Sensor Performance

There are at least two important aspects related to the sensors performance. First, as with the other solutions, the accuracy of the sensor can be a potential problem and source of control errors. Second, it is important that the sensor respond to the pollutant that is present. This implies that either the pollutant is known and a sensor sensitive to that pollutant is available, or that the sensor is sensitive over a broad range of pollutant sources.

One last consideration for filtration solutions is that the filter is capable of filtering the pollutants that are present. If the pollutant sources are known this may not be a problem; but if the pollutant source is not known, finding a filter to meet the specific needs of the given situation may be a problem. Most filters do not perform consistently for various pollutant sources.

CONCLUSIONS

Many new regulations are being proposed for work environments. If implemented, these regulations can have significant consequences for the design and operation of building systems. With the proliferation of microprocessor based controls for heating, ventilating and air conditioning systems, and the availability of pollutant sensors, new opportunities exist to simultaneous consider thermal comfort and indoor air quality. The design and operation of HVAC system should

PERFORMANCE ANALYSIS FOR COMMERCIALLY AVAILABLE CO_2 SENSORS

By Jim Jones,[1] Darren Meyers,[2] Harmohindar Singh,[3] and Peter Rojeski[4]

ABSTRACT: This paper describes the results for the first phase of a research program intended to investigate a popular ventilation control strategy known as demand-controlled ventilation (DCV). Before investigating various control strategies for DCV, an appropriate pollutant sensing device was necessary. Preliminarily, several commercial-grade CO_2 sensors from various manufacturers were qualitatively evaluated. The manufacturer with the "best" sensor was then identified. Twenty-nine CO_2 sensors from this manufacturer were calibrated using recommended calibration protocol. Sensor performance was evaluated for steady-state and transient conditions in a well-mixed environmental chamber. The results suggested the sensors had larger than expected variance and needed both steady-state and transient normalization before further studies could be conducted. This paper describes the experimental procedures, comparison of sensor performance, normalization procedure, and implications for DCV control.

INTRODUCTION

The widespread concerns for the health, well-being, and productivity of building occupants have been an essential element in maintaining good indoor air quality (IAQ) at home and in the workplace (*ASHRAE* 1989). In most cases, improvements in IAQ are accomplished by increasing the outdoor air (OA) to the building. Although adequate ventilation is not a panacea for ensuring good IAQ, inadequate ventilation must be avoided because of the costs incurred due to decreased occupant productivity, occupant health care, and possible litigation (Gaztech 1992b). Therefore, it is necessary to supply minimum OA ventilation rates to the indoor environment that are consistent with acceptable IAQ while avoiding the energy penalties associated with conditioning large volumes of OA.

Studies of building occupancy have shown that CO_2 is exhaled at a rate dependent on occupant density, activity level, and diet (MacHattie 1960). As a result, in buildings where the occupants are the primary pollutant source, the Indoor Air Quality Procedure of *ASHRAE* (1989b) allows for the control of outdoor ventilation air based on the use of CO_2 as a surrogate measure of occupancy. This has recently led to the increased application of relatively accurate, commercially available CO_2 sensors. This trend is likely to continue as the energy-savings potential of demand-controlled ventilation (DCV) becomes widely recognized.

DCV is a control approach that modulates the position of the outdoor ventilation air dampers in response to sensed levels of an indoor pollutant. In spaces where the occupants are the primary pollutant source, CO_2 has been used as a surrogate indicator of pollutant concentration. When other sources are present, sensors in addition to CO_2 should be used. While this control strategy has been shown to reduce energy consumption when compared to conventional ventilation strategies, some fundamental questions concerning the implementation of DCV remain.

- Do these sensors respond accurately over a range of CO_2 concentrations?
- What are the transient response characteristics of the sensors?
- Are the sensors susceptible to drift over the life of the building?
- How complicated is the calibration of such a device?
- Can we depend on these sensors to depict the occupancy pattern of the space for DCV applications?
- Where is the optimal location(s) of such sensors in building spaces?

Therefore, a research program was undertaken to investigate these issues related to DCV.

The original objective of the research project was to investigate the interaction between occupancy patterns and DCV, and to determine the optimal location for a CO_2 sensor used to control OA flow in a DCV strategy. It was hypothesized that CO_2 sensor performance might be affected by its location in the room and its position relative to the supply and return grilles. It was also hypothesized that since the CO_2 in the supply air probably differed from the room concentration, stratification might occur and that a perfectly mixed assumption would be untrue. Therefore, a test was devised in which CO_2 sensors are to be placed in various locations in a well-mixed chamber where CO_2 concentrations of the supply air and the room are closely regulated. Of interest was the effect of sensor location on both steady-state and transient responses. A concern for this research was the magnitude of the output variance of the sample of CO_2 sensors to the actual variance of CO_2 for a range of test conditions. If the test sensors lacked sufficient accuracy, then no inferences could be drawn from the results. Therefore, the reliability of the sensors had to be verified before further testing could be conducted. Furthermore, if the sensors were found to perform significantly worse than manufacturer's specifications, then their applicability to automated building control strategies could be questioned.

An important consideration for the research program was the performance of the CO_2 sensor. Since there were several products on the market at a different price (ranging from $500 to $1,500), a preliminary evaluation of sensors was made to determine the most cost-effective. Five different sensor models from three different manufacturers were purchased and tested. Qualitatively evaluated criteria included the cost, number of years in business, sensor technology, accuracy and drift, and ease of calibration.

After determining the most cost-effective sensor, 29 CO_2 sensors from one manufacturer were calibrated using 28 recommended calibration protocols, (Telaire 1994) and 27 were arranged in a grid as shown in Fig. 1.

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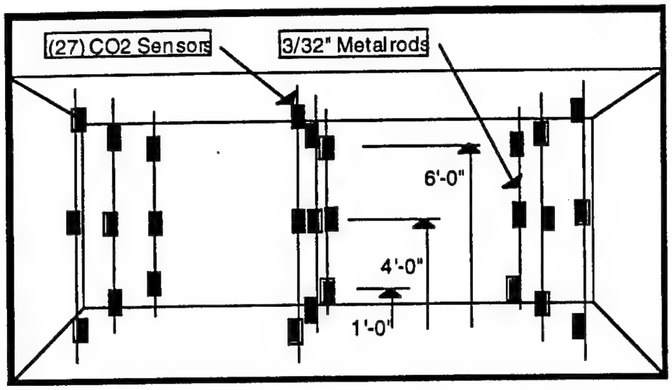

FIG. 1. Environmental Chamber Sensor Location

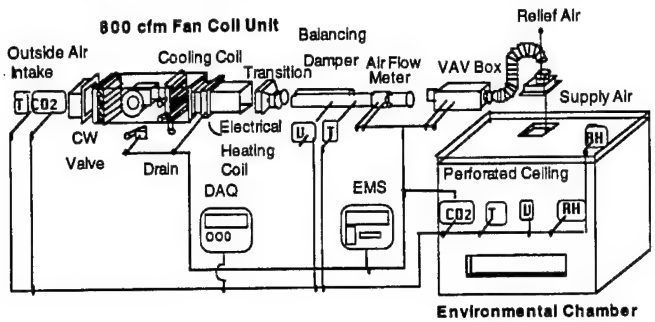

FIG. 2. Experimental Setup

Prior to initiating the test to determine the effects of sensor location, a steady-state test with 100% recirculated room air in a well-mixed chamber environment was conducted to evaluate the performance of 27 sensors. Experiments were performed in the Indoor Environmental Quality Laboratory for a geometrically representative, single occupant office, a space: 3.65 × 3.65 × 2.44 m. The chamber is constructed with exterior aluminum, an exterior vapor barrier, R-11 insulation, an interior vapor barrier, and interior stainless steel. Construction materials were selected to minimize offgassing and sink effects. The experiments required altering the environmental chamber and reconfiguring the heating, ventilation, and air-conditioning system (see Fig. 2).

A small fan coil unit (approximately 800 cfm) was installed and configured with a fractional, air-cooled chiller (3 t) to provide conditioned or nonconditioned OA to the environmental chamber. A reheating coil was installed to control the temperature of the OA entering the environmental chamber. Relative humidity was typically between 40 and 60%, and within the manufacturer's suggested operating range. Physical alterations to the chamber included creating an opening in the ceiling. This opening allowed for the access of supply air from the air-handling unit and the egress of the exhaust air from the chamber.

A plenum ceiling was installed in the chamber consisting of 17 stainless steel, 0.61 × 1.22 m lay-in ceiling tiles, each with 72 19 mm diameter holes. Again, stainless steel ceiling tiles were chosen to maintain the IAQ integrity of the chamber and minimize offgassing and sink effects. The matrix of perforations in the ceiling theoretically creates uniformity in the RA flow pattern throughout the chamber and allows for high ventilation effectiveness.

The three-dimensional matrix of 27 CO_2 sensors (excluding a reference sensor and the OA CO_2) and 27 T-type thermocouples were arranged in a matrix 2.74 × 2.74 × 1.83 m. Each sensor was independently powered and wired to a laboratory data-acquisition (DAQ) system.

An "H-shaped" dispersion apparatus was designed and constructed to deliver pure CO_2 uniformly to the chamber during tracer testing. The apparatus, with vertical legs spanning 3.65 m horizontal legs of 1.83 m, and dispersion jets at 305 mm OC, was located just below the suspended ceiling. By varying the length of time that CO_2 was introduced into the sealed chamber, the concentration levels could be easily controlled. For example, by supplying pure CO_2 to the chamber at 68.9 kPa for 60 s, the concentration could be increased from ambient to approximately 1,000 ppm. Mixing of the CO_2 in the chamber was accomplished by operating two oscillating fans. The fans were allowed to run throughout the duration of the test to maintain "well-mixed" conditions. Temperatures at all of the sensor locations were monitored and observed. Thermal uniformity, shown by a small variance (less than 0.5°C) in the thermocouple readings, provided evidence of a well-mixed environment.

The DAQ platform for opertion of the acquisition software operated on a computer with 8M/500Mb memory and CD ROM capability. The DAQ monitored 27 individual CO_2 sensors, 27 T-type thermocouples, nine omni-directional hot-wire anemometers, and two relative humidity sensors. DAQ has the capabilities to monitor numerous data channels at adjustable acquisition rates (in seconds), monitor and multiplex various sensor types (voltage, t-thermocouples, current, etc.), set channel high/low signal limits, monitor independent reference and real-time channel readings (via analog, digital, graphical, and chart form), incorporate mathematical signal conditioning before test data is written to file, indicate individual data tracks using colors or symbols, and record and save test data to a spreadsheet file with headings.

COMPARISON OF SENSOR PERFORMANCE

Sensor accuracy and repeatability are important for proper operation of DCV and essential for laboratory testing. Therefore, it was necessary that the 27 separate CO_2 sensors perform well during steady-state and transient conditions, and that their variance be small relative to the variations induced by the test conditions, transient meaning time response to a higher or lower CO_2 (ppm) shock. All 27 sensors were calibrated to manufacturer's specifications. The sample of sensors included

1. Eighteen model A-1, nondispersive infrared, wall-mounted, CO_2, 0-2 V dc output, 0–2,000 ppm, accurate to ±5% full scale or ±50 ppm, ±100 ppm annual drift
2. Four model A-2, nondispersive infrared, wall-mounted, CO_2 sensor, 4–20 mA output, 0–2,000 ppm, accurate to larger of ±5% full scale or ±50 ppm, ±100 ppm annual drift
3. Three model B, nondispersive infrared, wall-mounted, CO_2 sensor, 4–20 mA output, 0–5,000 ppm, accurate to larger of ±5% full scale or ±100 ppm, ±100 ppm annual drift
4. One model C-1, nondispersive infrared, duct-mounted, CO_2 sensor, 0–10 V dc output, 0–2,000 ppm, accurate to larger of ±5% full scale ±100 ppm annual drift
5. One model C-2, nondispersive infrared, wall-mounted, CO_2 sensor, 0–10 V dc output, 0–2,000 ppm, accurate to larger of ±5% full scale ±100 ppm annual drift

Steady State

Upon completion of the full calibration procedures, the sensors' steady-state readings of CO_2 concentrations in a sealed, well-mixed chamber were observed for various conditions ranging from approximately 400 to 2,000 ppm. Pure CO_2 was introduced into the chamber for various lengths of time to achieve the desired CO_2 concentration. For example, by supplying pure CO_2 for 60 s, a uniform concentration of approximately 1,000 ppm was achieved. Concentrations were main-

tained within a few parts per million for several minutes and recorded. Fig. 4 shows the monitored levels of the sample sensors at ambient conditions. As shown, the CO_2 concentrations ranged from approximately 200 to 550 ppm, a range of 350 ppm (see Fig. 3). This was much greater than the manufacturer's specified range and was unacceptable for meeting the objects of the DCV study. Even though the chamber was thought to be well mixed, the results were so highly variable that additional tests were made with sensor locations switched. These subsequent tests confirmed that the sensors were performing erratically independent of their location in the chamber.

Transient State

In addition to steady state, the transient response of the sample sensors was observed. Although we felt that we could correct the steady-state performance of the sensors, before we did so we wanted to check their transient response characteristics. Although the manufacturer did not specify the transient performance of the sensors, one would assume that since they were similar models, their transient response characteristics would be similar.

A process was developed to assist in the evaluation of the transient characteristics of each sensor. Rate-performance curves were created for each sensor by supplying the sensor with a known, zero CO_2 concentration (100% N_2) and then "shocking" the sensor with a "high-span" limit CO_2 concentration, which in the case of the CO_2 sensors in question were 2,000 ppm CO_2. The sensor output was observed until steady-state conditions were reached at the 2,000 ppm concentration. Thus, a picture of each sensor's response characteristics over its entire range of measurement could be evaluated. Rate-performance curve development took anywhere from 30 to 45 min per sensor.

Although the manufacturer's calibration protocol was followed, it can be seen that the time constants for individual sensors ranged from 20 s to 6 min (see Fig. 4). Sensor-response times from a zero CO_2 concentration to a "high-span" CO_2 concentration (2,000 ppm) varied anywhere from 50 s to 12.5 min. It was also noted that response times varied within the same model.

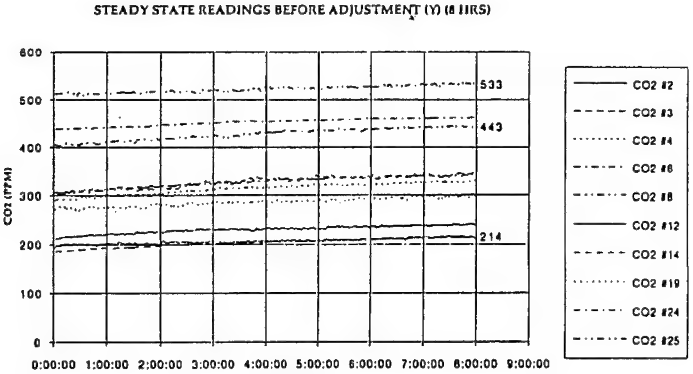

FIG. 3. Steady-State Data after Full Calibration

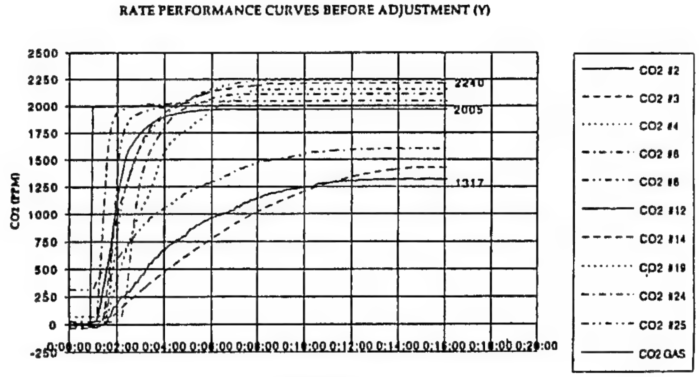

FIG. 4. Transient Data after Full Calibration

NORMALIZATION PROCEDURE

Since the sensor performance under both steady-state and transient modes produced variations that were higher than the expected difference in CO_2 concentrations resulting from various test conditions, the original study to determine the optimal sensor location was postponed, and the new objective became the "normalization" of the sensor response using a mathematical procedure. The procedure involved modeling the difference between the study sensor and a reference sensor for both steady-state and transient conditions. By normalizing the sensor output, it was thought that the variance in their readings could be reduced to a value that would provide greater reliance on the inferences drawn from subsequent tests.

Choice of Reference Sensor

Following the preliminary findings that suggested the need for a normalization procedure, a "reference" sensor was needed. This would allow the output of the sample of study sensors to be normalized to that of the reference. The budget for this project did not allow for the purchase of a research grade CO_2 sensor, which costs in excess of $5,000. Therefore, the reference was chosen from the batch of commercial sensors and was selected as that sensor that was nearest to the mean of all sensors that were not considered outliers, was most accurate over the entire range of CO_2, had an experimentally derived slope and offset for voltage versus concentration nearest to manufacturer's suggested slope and offset, and was among the quickest to respond.

To determine the sensor voltage output to concentration relationship, three concentration levels were observed: zero concentration (100% N), 800 ppm, and 2,000 ppm. A gas mixture with a known CO_2 concentration (0, 800, and 2,000 ppm) was fed directly to the sensor through tygon tubing. The corresponding voltage output was recorded. Linear regression was then applied to determine the slope and offset for each sensor. The sensors that most closely approximated the manufacturer's suggested slope and offset were identified as possible reference sensors.

Selection of the reference sensor was also based on the subjective evaluation of the rate-performance data. The optimal sensor would have a relatively quick response time to a change in CO_2 concentration (C_n) of ($\leq$2 min), preferably quicker. As previously described, each sensor was "shocked" with 2,000 ppm CO_2 after being fed 100% N. The time-series response of the sensor output was recorded and observed. The sensors that achieved steady output at the 2,000 ppm level within 2 min were identified as potential reference sensors.

Statistical analysis of the steady-state and transient conditions was then performed. The "best" sensor was chosen from the sample of sensors nearest the statistical mean of the steady-state data from all sensors, and which was among the quickest to respond, and most closely approximated the manufacturer's output to concentration equation (see Table 1).

As previously shown, the performance of many of the sample sensors did not meet manufacturers' claims for accuracy. Consequently, a procedure was developed to normalize the CO_2 concentrations to that of the reference sensor. The normalization procedure for commercially available CO_2 sensors should consider steady-state adjustments and transient adjustments.

TABLE 1. "Best" Sensor (Model A)

Test CO_2 (ppm) (1)	Average voltage (V) (2)	Indicated CO_2 (ppm) (3)
0	0.0293	−2.97
810	0.8363	815.03
2,000	2.0033	1,997.94

Note: Instrument slope (ppm = 1,000 V + 0); Laboratory slope (ppm = 1,013.6 V − 33.6); Response time = 150 s.

Steady-State Normalization

For the steady-state normalization a CO_2 tracer test was performed for four CO_2 seeding concentrations (2,000, 1,500, 1,000, and 500 ppm) in the environmental chamber and observed over an 8 h period. Pure CO_2 was delivered to the 32.6 m^3 (3.65 × 3.65 × 2.44 m) chamber at 10 psi for 00:02.00, 00:01.30, 00:01.00, and 00:00.30 (120, 90, 60, and 30 s) to obtain "well-mixed," average initial CO_2 seeding concentrations of 1,996.14, 1,521.49, 1,036.09, and 495.76 ppm, respectively. Mixing in the chamber was accomplished via two oscillating fans. The fans were allowed to run throughout the duration of the test to maintain "well-mixed" conditions. Minor variance of the temperature measurements in the environmental chamber verified the "well-mixed" condition.

For steady-state conditions when exposed to the same CO_2 levels, the output of all sample sensors should be nearly equal. When this is not the case, the output from the study sensor must be adjusted to correspond to that of the reference sensor as shown in Fig. 5. For this, the deviation from a reference value (Y_R) taken as the output of the reference sensor over a range of CO_2 levels should be modeled for each sensor value (Y). The objective was to express the correction factor ($Y' = Y_R - Y$) in terms of the output of the sensor in question (Y) while recognizing that the necessary adjustment may depend on the CO_2 concentration level

$$Y' = Y_R - Y = \beta_0 + \beta_1 Y \qquad (1)$$

The data were plotted with the difference between the reference sensor reading and the study sensor ($Y_R - Y$) in parts per million as the ordinate and the study sensor reading (Y) in parts per million as the abscissa (see Fig. 6). Under steady-state conditions, Y could then be used to produce a normalized study sensor concentration (Y^*), adjusting it back to the "correct" reference sensor reading

$$Y^* = Y + Y' \qquad (2)$$

Upon subjective evaluation of Y' versus Y from the preliminary data, four distinct patterns emerged. These are shown in Fig. 7. Out of the 27 sensors, 24 were involved in the steady-state evaluation. The remaining three were the reference, sensor, the OA CO_2 sensor, and one sensor that was out for repair.

Pattern I was linear. With sensors having this characteristic (six out of 24), Y' was largest during the 2,000 ppm CO_2 seeding and smallest during the 500 ppm CO_2 seeding. All, six out of six, of the sensors with this characteristic became more accurate as CO_2 concentration decreased. Sensors with this type of response were the simplest to normalize. Ordinary least squares (OLS) linear regression was performed as in (1).

Pattern II formed a checkmark shape declining down and to the left. With sensors having this characteristic (12 out of 24), Y' was largest during the 2,000 and 1,500 ppm CO_2 seedings, and smallest during the 1,000 ppm CO_2 seeding. Eight out of 12 sensors with this characteristic "bottomed out," or became more accurate, as the chamber conditions grew nearer to 1,000 ppm CO_2 ± 100 ppm. Three out of 12 sensors with this characteristic became more accurate as the chamber conditions grew nearer to 500 ppm CO_2 ± 100 ppm. Most, 10 out of 12, of the sensors with this characteristic were closer to the reference sensor during chamber conditions below 1,500 ppm CO_2 ± 100 ppm. Sensors with this type of response required piecewise OLS linear regression for the steady-state portion of the final normalization model. For this, two correction-factor models are derived, one for each portion of the CO_2 range, i.e., OLS linear regression performed on data from 0 to 800 ppm CO_2 and a second analysis for the data from 800 to 2,000 ppm CO_2 (the point of inflection being located near 800 ppm). Therefore, the sensor would follow the first corrective model between 0 and 800 ppm CO_2, and the second corrective model between 801 and 2,000 ppm CO_2.

Pattern III formed a reversed checkmark shape declining down and to the right. With sensors having this characteristic (three out of 24), Y' was largest during the 500 and 1,000 ppm CO_2 seedings, and smallest during the 1,500 and 2,000 ppm CO_2 seedings. Two out of three sensors with this characteristic "bottomed out," or became more accurate as the chamber conditions grew nearer to 1,500 ppm CO_2 ± 100 ppm. One out of three sensors with this characteristic became more accurate as the chamber conditions grew nearer to 2,000 ppm CO_2 ± 100 ppm. All, three out of three, sensors with this characteristic were closer to the reference sensor during chamber conditions above 1,500 ppm CO_2 ± 100 ppm. Sensors with this type of response also required piecewise OLS linear regression for the steady-state portion of the final model (the point of inflection being located near 1,500 ppm).

Pattern IV formed an upside-down "U" shape. With sen-

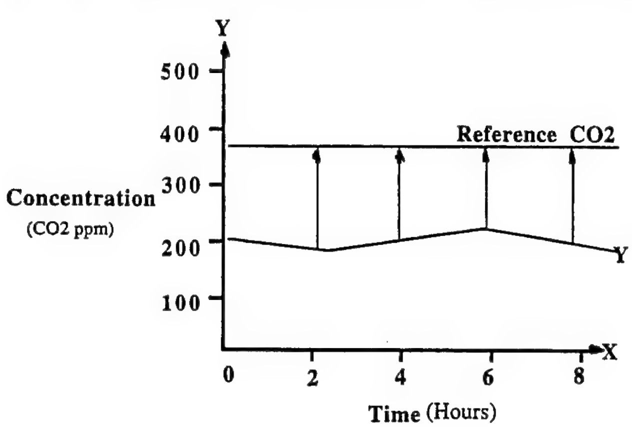

FIG. 5. Normalization Process for Steady-State Adjustments

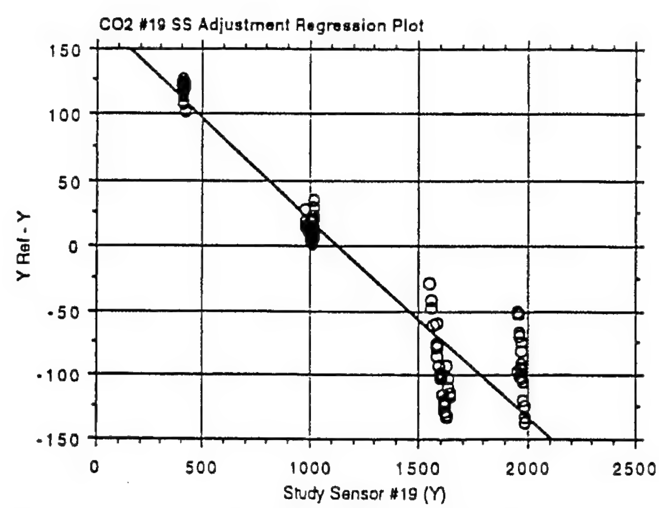

FIG. 6. CO_2 Sensor Number 19 Steady-State Adjustment Scatter Plot for $Y_R - Y$ and Y

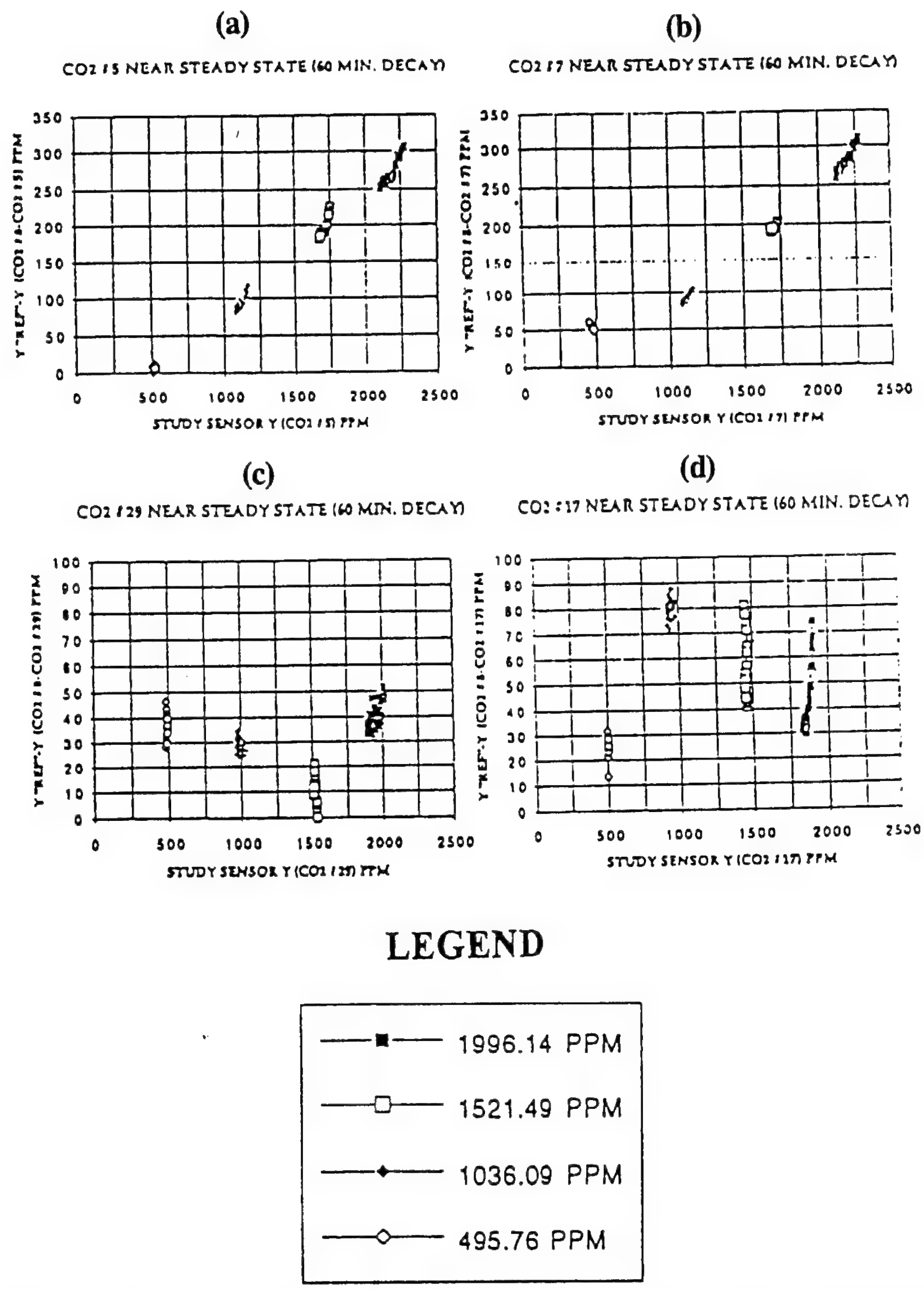

FIG. 7. Patterns I–IV Steady-State Sensor Deviations (Y) for Normalization to Reference Sensor ppm (Y_R): (a) Pattern I; (b) Pattern II; (c) Pattern III; (d) Pattern IV

sors having this characteristic (three out of 24), Y' was largest during the 1,000 ppm CO_2 seeding, and smallest during the 500 and 2,000 ppm CO_2 seedings. All, three out of three, sensors with this characteristic were least accurate between 800 and 1,200 ppm $CO_2 \pm 100$ ppm. Each sensor was closer to the reference sensor during chamber conditions below 500 ppm $CO_2 \pm 100$ ppm and above 1,500 ppm $CO_2 \pm 100$ ppm. Sensors with this type of response used piecewise OLS linear regression for the steady-state portion of the final normalization model (the point of inflection being located near 1,000 ppm).

Final Steady-State Adjustments

After analyzing each sensor with its associated response pattern and applying the appropriate modeling technique, a steady-state normalization was achieved. Fig. 8 shows the CO_2 concentrations after applying the steady-state normalization. As shown, the variation in sensor output has been reduced to within the manufacturer's specification.

Transient Normalization

The second adjustment was made so that the study CO_2 sensor output, now (Y^*), corresponds to the response of the reference sensor (Y_R) under transient conditions. The process is shown in Fig. 9. The difference was modeled over time, time (t) versus time ($t - 1$), as a function of the rate of change for the study sensor. Again, the objective was to express the correction factor (Y'') in terms of the output of the sensor in question (Y). In this case, however, the correction factor (Y'') is related to the rate of change of the sensor output. This is expressed by the difference between the current and previous value. As the difference increases, a larger adjustment is applied. Conversely, when steady-state conditions exist ($Y_t^* - Y_{t-1}^* = 0$) and no transient adjustment is required, the normalized sensor output reverts to the value when only applying the

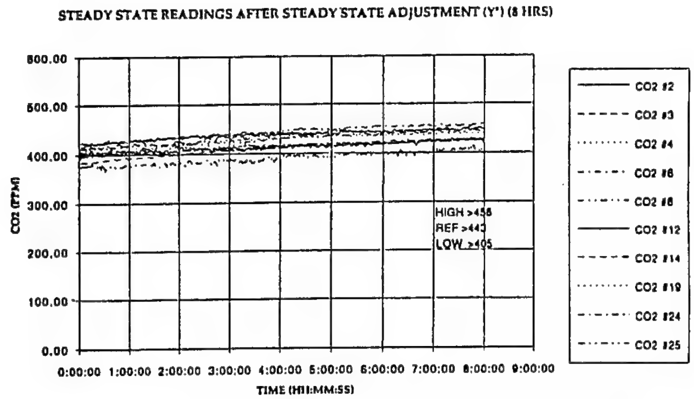

FIG. 8. Readings after Steady-State Adjustment (Y^*)

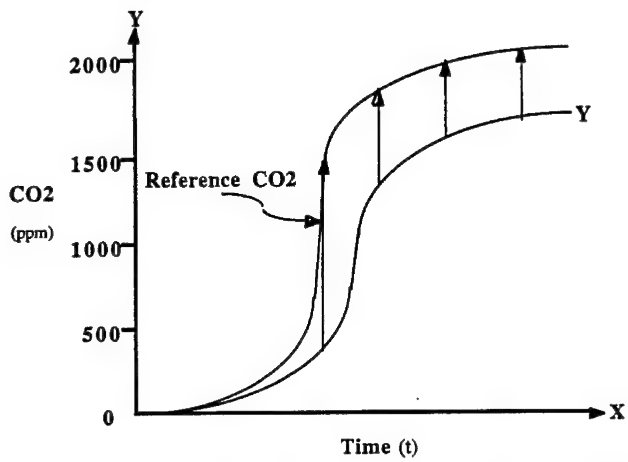

FIG. 9. Process for Adjusting Study Sensor Output to That of Reference Sensor

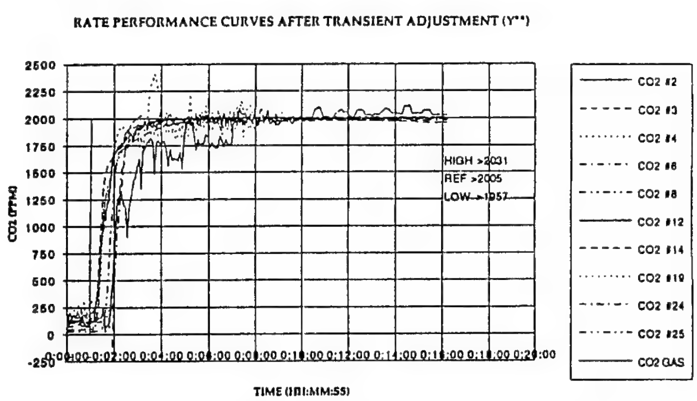

FIG. 10. Readings after Steady-State and Transient Adjustment (Y'')

steady-state adjustment. For this, (3) is derived without an intercept

$$Y'' = Y_R - Y_t^* = \beta_1^*(Y_t^* - Y_{t-1}^*) \tag{3}$$

The modeling procedure involved an autoregressive process by using "n" lagged observations of the time-series differences between (Y^*) to predict the current observation

$$Y_R - Y_t^* = z = {}_1a + {}_2a_1(Y_t^* - Y_{t-1}^*) + {}_3a_2(Y_{t-1}^* - Y_{t-2}^*) + \cdots \tag{4}$$

It may be easier to think of the transient portion of the model as an OLS linear regression model in which the current time-series observation is regressed on the preceding time-series observation. Generally it was found that a first-order process (only considering the first lagged value) was sufficient to describe the process.

The influence of a past event (or output concentration, Y_{t-1}^*) on present events (present concentration, Y^*) diminishes as time passes. While the random shock stays in the process indefinitely, its impact diminishes exponentially over time. After one observation and/or correction, the impact of a is only a fraction of its initial impact. By time t, the impact of a, the random event, is so small that we may think of it as zero.

Fig. 10 shows the output of the study sensors after applying the transient adjustment. As shown, the time constants for the study sensors have typically been reduced to less than a minute and the responses approximate that of the reference sensor.

Final Model

Applying (1), (2), and (3), the normalized output for the study sensor considering both the steady-state and transient conditions will be

$$\text{output} = [Y_t + (\beta_0 + \beta_{11}Y_t)] + \{\beta_{12}^*[(Y_t + \beta_0 + \beta_{11}Y_t) - (Y_{t-1} + \beta_0 + \beta_{11}Y_{t-1})]\} \tag{5}$$

Verification of the final model was scrutinized with both the experimental responses and predicted responses of several CO_2 sensors. Success involved close correlation of the experimental responses and predicted responses.

IMPLICATIONS FOR SYSTEM CONTROL

The results presented in this paper show the variance in output of a popular, commercially available CO_2 sensor. The sensor output is typically used as a surrogate monitor of OA ventilation and interrelated IAQ issues. Building operators should, at least, recognize the potential of the performance differences shown in this paper.

For instance, during the application of these sensors in a multizone environment using discriminator control to vary OA ventilation levels, the inherent intractability of the sensors could have implications on air-conditioning and air-transport energy costs. For example, if one sensor in the multizone matrix is an outlier (high or low), ventilation demand could be affected accordingly throughout a significant portion of the facility.

Results from this study indicate that it is not uncommon for CO_2 sensor output to vary by more than ± 50 ppm under well-mixed conditions. This variance can potentially impact the ability to meet the desired IAQ conditions as well as maximize the benefit/cost of a DCV system. This is particularly true when considering that the typical control range for CO_2 will be between about 500 and 1,000 ppm. If the sensor is in error by 100 ppm, as was shown to be possible by this study, the control action could be in error by as much as 25% of the control range. For example, if a sensor incorrectly indicates a CO_2 concentration 100 ppm lower than the actual level, CO_2 levels will be greater than 1,000 ppm and less outdoor ventilation air will be supplied than is actually needed. If, on the other hand, the sensor incorrectly indicates a CO_2 concentration 100 ppm higher than actual, IAQ conditions will be maintained at the cost of uneccessarily conditioning excess outdoor air. This is because, as the sensor incorrectly indicates a CO_2 concentration above 1,000 ppm, the OA dampers will open to provide more ventilation air and lower the CO_2 concentration. Since the actual CO_2 concentrations were below the limiting upper level of 1,000 ppm, opening the dampers was unnecessary.

Building operators could use this information to adapt their facility's energy management system to compensate for the sensor's lag and/or lead time until a comfortable solution is

achieved. Convincing effects with regard to the facility's OA ventilation demand, energy use, and occupant comfort/productivity could be attained. The ramifications of success significantly affect professionals in the building and design community who currently use or plan to apply control strategies utilizing this popular CO_2 sensor.

Two additiional points should be made. First, the large variance of the study sensors suggests that their in-situ performance for DCV should be periodically checked. For this, a facility manager might use a recently calibrated hand-held sensor to monitor CO_2 levels throughout the building's occupied spaces. This should be done at different locations, times of the day, and days of the week. The monitored values should be below the target concentration level set in the DCV control logic. Second, due to the time-consuming review process for this paper, the technology for CO_2 sensing seems to have improved since this paper was originally submitted. Recent experiences by the writers seem to indicate that new sensors perform better than the earlier versions presented here, although a similar analysis is needed.

ACKNOWLEDGMENTS

The writers would like to thank the U.S. Department of Defense, Telaire Systems, Inc., the Center for Indoor Air Research, and the Honeywell Corporation for their support of the Indoor Air Quality Research Program at North Carolina A&T State University, Greensboro.

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ENERGY COST COMPARISON FOR DEMAND CONTROLLED VENTILATION VS. 20 CFM PER PERSON

J. JONES H. SINGH G. WELLMAN

ABSTRACT

This paper presents the results of an investigation to compare the annual energy consumption for demand controlled ventilation and constant ventilation flow at 20 cfm per person. The analysis was conducted using experimental data to estimate the demand for ventilation air flow for different occupancy patterns, and computer simulation to estimate energy consumption. Over 90 simulations were performed for three different climatological locations.

INTRODUCTION

Recently, as a result of concerns for Indoor Air Quality (IAQ) and energy conservation, Demand Controlled Ventilation (DCV) strategies for heating, ventilating, and air-conditioning (HVAC) systems have become popular. This is because most HVAC systems are designed for based on the Ventilation Rate Procedure of ASHRAE Standard 62-1989[1]. The VRP prescribes a ventilation flow based on design occupancy and required minimum flow rates per person. For example, offices must be ventilated with at least 20 cfm per person. If the occupancy schedules are such that only a fraction of the design number of people are typically present, or the occupancy patterns vary throughout the day, then much of the time the space may be overventilated and DCV may be a cost effective strategy. For spaces with variable occupancy DCV adjusts the flow of outdoor air based on the actual number of occupants present. This is achieved as a result of natural metabolic processes occurring in the human body where carbon dioxide is exhaled at a fairly predictable rate. Consequently, indoor air carbon dioxide (CO_2) concentration is often used as a surrogate measure of occupancy such that as inside CO_2 levels increase the outdoor air intake dampers open to allow for more flow. By varying the flow in this way less heating and cooling energy is needed to condition the outdoor ventilation air when compared to constant flow for 20 cfm per person at design occupancy.

An important issue for the implementation of demand controlled ventilation is its cost effectiveness when compared to a less complicated control strategy using a fixed rate of 20 cfm per person. Demand control requires a computer based system with appropriate hardware including sensors. Currently CO_2 sensors start at about $500 each. Control points through an Energy Management System might be $200 each. These costs when added to the installation and maintenance costs associated with sensor calibration and replacement can reduce the benefit/cost of DCV strategies. The savings from DCV depends on many factors including: HVAC system design and operating characteristics, climate, occupancy density, and occupancy pattern, to mention only a few. In an effort to better understand the interactions among these factors an analysis was performed using experimental results and computer simulation.

METHODOLOGY

The evaluation of energy consumption for demand controlled ventilation versus 20 cfm per person was carried out using experimental data and computer simulation.

Before energy consumption could be estimated, patterns of outdoor air flow in relation to occupancy had to be established. To estimate the rate of outdoor ventilation air intake for various occupancy patterns using demand controlled ventilation, experiments were performed in the Indoor Environmental Quality Research Laboratory at North Carolina A&T State University. Two chambers were constructed for studying the interaction of the HVAC system characteristics and occupancy patterns. The chamber dimensions were 11'-6" width by 16'-0" length by 8'-0" height and were selected as representative of a single or double occupancy office. Air was supplied to both chambers through a 500 cfm fan coil unit. The air flow into the chambers were balanced and represented approximately 1.2 cfm per square foot of floor area which was thought to represent design conditions for a typical office. Air was returned through a ducted ceiling mounted return grille. The HVAC unit was configured with return, relief and outdoor air intake dampers that were controlled through a RobertShaw computer-based Energy Management System (EMS). The damper position and flow of outdoor air were controlled based on the sensed level of CO_2. A CO_2 sensor was located in the common return air duct serving both chambers. This provided an average concentration for CO_2 in both chambers, and based on a previous study, was selected as the most appropriate controller location.[2] The outdoor air intake dampers were positioned from fully opened to fully closed based on the CO_2 level. The OA dampers begin to open at 600 ppm and are fully opened at 1000 ppm. The damper position was linearly related to the concentration between 600 and 1000 ppm. Supply, return, and outdoor air flow rates and temperatures were measured and recorded every thirty seconds throughout each test period.

Tests were performed for various occupancy patterns. Use of live occupants was not practical therefore occupancy patterns were simulated by controlling the flow of carbon dioxide through an Omega FMA-100 mass flow controller and meter. Pure CO_2 was taken from a cylinder, heated through a hot water bath, passed through the mass flow controller to the test chamber where it was discharged through a nozzle. The CO_2 supply tube was wrapped with heat tape near the discharge location to bring the CO_2 temperature to approximately 95F. The discharge nozzle was mounted on an oscillator to simulate the head movement of an occupant. The flow rate of CO_2 was based on an assumed production rate of 0.3 L/m per person for office activities. The mass flow controller was connected to the RobertShaw EMS which allowed for automatic scheduling. Occupancy patterns representing 85, 75 and 50 percent average occupancy were simulated for each six hour test period. For example, 85 percent occupancy meant that CO_2 was supplied to the chamber during 85 percent of the six hours (5.1 hours) and was off for the remaining 15 percent of the time (0.9 hours). The 85 percent occupancy pattern most closely approximates a typical office environment where approximately 15 percent of the occupants will be sick, on vacation, or out of the office on business. The 75 percent occupancy level might represent an office with moderate sales activities or faculty offices in educational institutions where the occupant is out of the office 25 percent of the time. The 50 percent occupancy pattern might be representative of the emerging "virtual office" where the employee is on the road as frequently as they are in the office.

Several experimental tests were performed for each occupancy level. The recorded outdoor air flow rates were averaged into hourly values for each set of tests for a given occupancy level. The averaged flow rates were then normalized based on 20 cfm per person flow. The resulting patterns are shown in Figure 1. As shown as the CO_2 levels build up after the beginning of the occupancy period the OA dampers begin to open. On average the OA damper will continue to open until a near equilibrium condition is achieved, possibly after a few hours. For each occupancy pattern (85, 75, or 50%) the curve was shifted down for the lunch hour to represent people leaving the building. All hourly values following the lunch period were also shifted downward. This shift was estimated to be approximately 5 percent of the 20 cfm/person flow which was based on experience and engineering

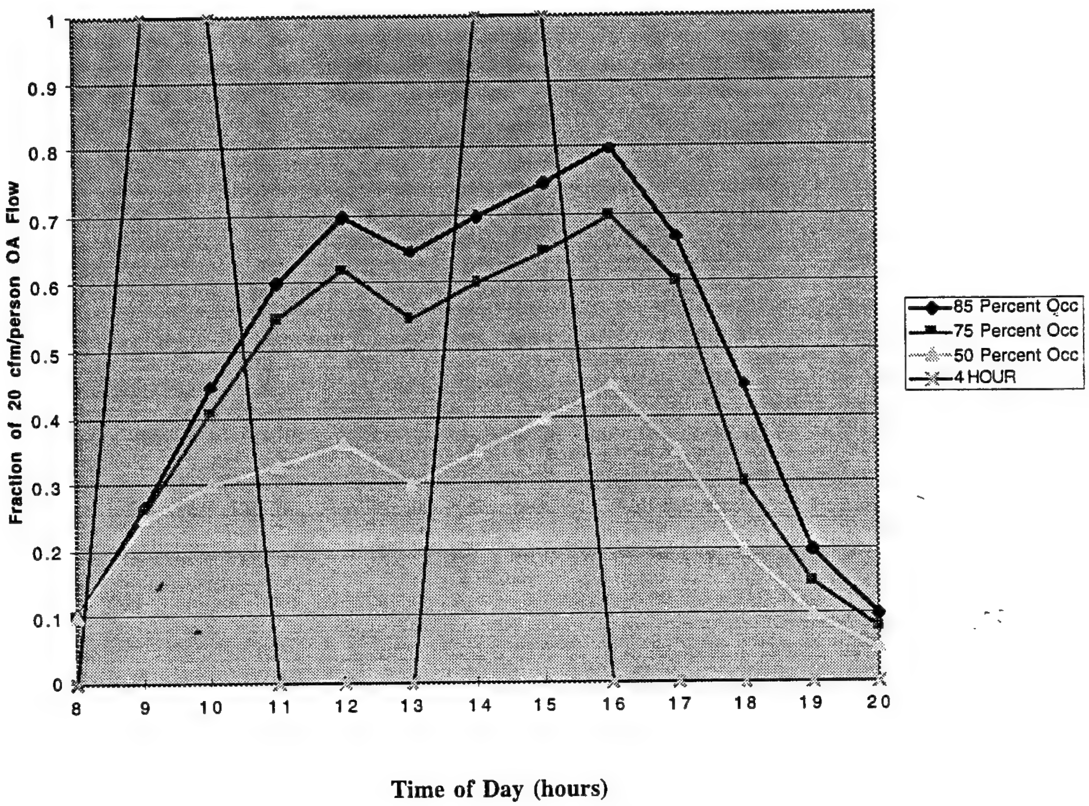

Figure 1. Experimentally Derived Outdoor Ventilation Air Flow Rates For Various Occupancy Patterns.

judgment. Estimation was necessary because a lunch break was not simulated in the CO_2 supply schedules used in the experimental study. The rate of decay for hours 18 through 20 was based on an assumed pattern of decreasing occupancy after normal operating hours.

Figure 1 shows one additional DCV control strategy where the HVAC system operates with 20 cfm per person for two hours in the morning and two hours in the afternoon, and no outdoor air flow for the remaining hours. This pattern might be representative of a conference room or auditorium, or possibly an infrequently used classroom building.

The experimentally derived ventilation air flow patterns were used to compare the energy consumption for various HVAC system characteristics, occupancy patterns, and climates. Energy consumption comparisons were made by performing annual simulations using the DOE2.1e computer software. Comparisons were made using a hypothetical three story, commercial office building. The building was of typical curtain wall construction with double pane ribbon windows. Construction materials and thermal performance of the walls and roof were selected to meet current codes and standards, and were representative of common build-lease practices. The building was slab-on-grade and had approximately 10,000 sqft. of floor area for each level for a total of 30,000 sqft. Lighting and equipment power densities were representative of commercial office buildings. Each floor was served by a separate packaged roof-top multizone HVAC system. The building and HVAC system modeling allowed for relative comparisons of the study variables and was not meant to indicate actual savings for any particular condition.

Simulations were performed for various combinations of HVAC system characteristics, occupancy patterns and climates. Although only multizone HVAC systems were simulated, two operating modes were used. For the first, the hot and cold deck temperatures were allowed to reset hourly in response to the zone having the largest heating or cooling demand (often referred to as discriminator control). For the second set of simulations no reset was used and hot and cold deck discharge temperatures were constant at 105 and 55F respectively. Primary heating was provided below 70F and cooling was available above 55F outdoor air temperature. Simulations were performed for HVAC systems operated with three different base levels of minimum outdoor air intake. These included 10, 20, and 40 percent of design flow as outdoor air. This might be representative of an office building with individual enclosed offices (10% OA), a medium density open plan office area (20% OA), and a conference or auditorium, or densely populated open plan office area (40% OA). For each of these base cases the minimum fraction of outdoor air was set to either 0.1, 0.2, or 0.4 throughout the HVAC system operating period. The HVAC system was on Monday through Friday from 7:00 a.m. to 8:00 p.m. DCV comparisons were made using each of these levels of outdoor air intake as a base level. All simulations allowed for outdoor air economizer control below 72F for free cooling.

For each set of HVAC system characteristics (Reset (Y or N) - %OA (10,20 or 40)), simulations were performed for a base case and for each outdoor air flow pattern shown in figure 1. Annual energy consumption was estimated for Miami, Florida; Greensboro, North Carolina; and Chicago Illinois. A total of 90 simulations were performed.

RESULTS AND DISCUSSION

The results of the simulations performed for the HVAC system operated without hot and cold deck temperature reset are shown in Figure 2 while those for the HVAC system operated with temperature reset are shown in Figure 3. The reductions in energy consumption are shown as a percentage of the base cases.

For all simulations the reductions ranged from less than 1.0 percent per year to nearly 35 percent.

Energy reductions related to the occupancy pattern indicate that by far the largest reductions, either with or without reset, were observed for the DCV control strategy with ventilation for two hours in the morning and two hours in the afternoon. This is probably most representative of an HVAC system serving a conference room or auditorium that is only occupied for a few hours each day. These energy reductions are most notable for Greensboro (GSO) and Chicago where between 20 and 35 percent lower consumption is shown. Although reductions are shown for Miami the percentage reduction is lower than for the other locations. For the three continuous occupancy patterns (85, 75 and 50 percent of design occupancy) the largest savings are shown for the 50 percent pattern, as expected. However, for HVAC systems with less than 20 percent base outdoor air, the reductions are less than 5 percent for all locations.

The base flow of outdoor air (10, 20 or 40%) can be influential in determining the savings from DCV. For example, figure 3 indicates that for HVAC systems with temperature reset and for the three continuous occupancy patterns, savings above 5 percent are not achieved except for the simulation with 40 percent outdoor air base ventilation air flow. For this situation savings over 15 percent are shown for the 75 and 50 percent occupancy patterns for Chicago. For the same conditions reductions greater than 10 percent are shown for Greensboro. This implies that DCV may be beneficial when the HVAC system has a

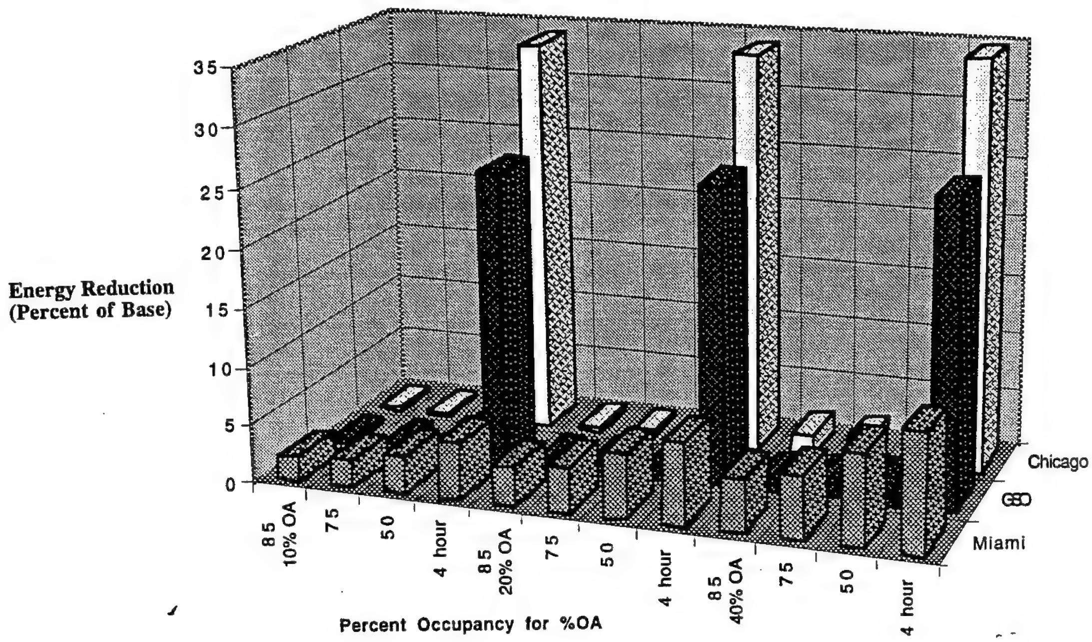

Figure 2. Comparison of Energy Consumption Reductions for HVAC Systems Operated Without Temperature Reset.

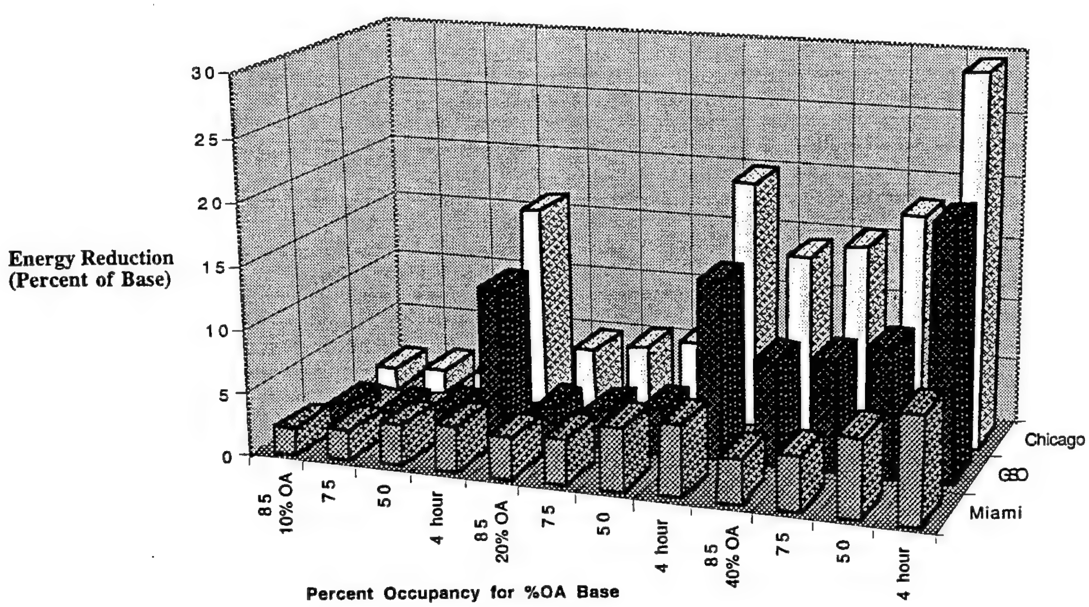

Figure 3. Comparison of Energy Cost Reductions for HVAC Systems Operated With Temperature Reset.

relatively large base flow of ventilation air flow, such as for an auditorium or densely populated open plan office. For buildings or HVAC zones with low to medium population density energy reductions from DCV may not be large enough to justify the installation costs.

Climate is an important factor in determining energy reductions for DCV. Generally, the more extreme the climate, and the farther the average outdoor air temperature is away from the indoor air temperature, the more savings can be achieved. Figure 3 indicates that with temperature reset the largest energy reductions are for Chicago. Care must be taken, however, to consider the interactions between the outdoor air temperature and the HVAC system design and operating characteristics. Depending on these characteristics the system may be more or less efficient for heating than for cooling. Figure 2, for example, indicates a different result when HVAC system temperature reset is not implemented. For this situation Miami has the largest reductions except for the system operated with 2 hours of morning and 2 hours of afternoon ventilation.

CONCLUSIONS

The results from this work suggest at least three important considerations for the cost/benefit of demand controlled ventilation. First, for buildings with typical occupant densities (10 or 20% OA base), demand controlled ventilation was shown to reduce energy consumption by less than 5 percent for all locations. Only for HVAC systems with high base ventilation air flows were savings in the 10 to 15 percent range. Second, the largest energy reductions were shown for an HVAC system that operated with 2 hours of morning and 2 hours of afternoon ventilation. This might be characteristic of a system serving an auditorium or conference room. For situations with continuous occupancy patterns (85, 75, or 50%) reductions were relatively low except for the high base flow condition (40% OA base). Therefore, DCV may not be cost effective for most typical office applications. Finally, the interactions between the HVAC system design and operating characteristics and the climate must be carefully considered. While figure 3 indicates that for HVAC systems with temperature reset the largest reduction can be achieved in Chicago, this is not indicated by figure 2 where simulations do not have temperature reset. Without reset figure 2 indicates that Miami has the largest reductions for the continuous DCV patterns. Depending on these interactions DCV may be more or less cost effective. These interactions should be carefully evaluated for the particular characteristics associated with the intended application.

One additional consideration for the implementation of demand controlled ventilation should be for building exhaust air flow rate and pressure balances. Most buildings have toilet and janitorial closet exhaust fans. In order to keep the building positively pressurized the volumetric flow of outdoor make-up air must be equal to or greater than the total exhaust flow rate. If the exhaust flow rate is greater than the design ventilation air flow rate based on the VRP of ASHRAE Standard 62-89 then the minimum flow of outdoor air will be based on the exhaust flow rate not on occupancy. For this condition DCV will not result in lower energy consumption unless the outdoor make-up air for the exhaust fans is conditioned separately.

ACKNOWLEDGMENTS

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EFFECT OF SENSOR PLACEMENT ON INDOOR AIR QUALITY FOR DEMAND CONTROLLED SYSTEMS

by

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INTRODUCTION

Recently, in an effort to maintain acceptable indoor air quality (IAQ) while minimizing energy consumption in buildings, new design and control strategies have emerged for heating, ventilating, and air conditioning (HVAC) systems. Among the most promising of these new solutions is Demand Controlled Ventilation (DCV). For spaces with highly variable occupancy, Demand Controlled Ventilation modulates the flow rate of outdoor ventilation air in response to the demands of the rooms being served. Auditoria, conference rooms, lounges, and some office environments are examples of spaces that can experience temporal variations in occupancy where the flow of outdoor ventilation air should be based on actual space conditions rather than design occupancy and 20 cfm per person. Vaculik [1], Bearg [2], Nabinger [3] and Schultz [4] are just a few that have discussed and demonstrated the use of Carbon Dioxide sensors to control outdoor ventilation air flow rate. A concern for these applications, however, is the cost. Currently, commercially available CO_2 sensors range in cost from over \$400 to \$1000 each. This may make the cost of installing a sensor in each space economically unattractive. If only one or a few sensors are installed to control many spaces, the controllability of the spaces served must be well understood. Therefore, an important question for HVAC system designers concerned with indoor air quality, and the application of a Demand Controlled Ventilation strategy, is - Where to locate the sensor to best control the zone pollutant levels? This question must be answered before a demand controlled ventilation strategy is implemented. A research program was undertaken to study three sensor locations; in-room, common ceiling return plenum, and common return duct. Tests were performed experimentally for each of the locations in two rooms representative of single or double occupant offices. Tests were performed for different occupancy schedules for the two spaces. It was hypothesized that the sensor located in the return air duct would provide lower average pollutant concentrations in the two test spaces when compared to the other sensor/controller locations.

METHODOLOGY

The determination of the optimal location for carbon dioxide sensors applied to demand controlled ventilation was studied experimentally in the Indoor Environmental Quality Laboratory at a southeast University. Experiments were conducted in two geometrically similar rooms. The rooms measured 11'-6" (3.2 m) width by 16'-0" (4.4 m) length by 8'-0" (2.2 m) height, with a 2'-0" (0.6 m) ceiling plenum, see Figure 1. The room walls and roof were constructed of aluminum panels and vinyl vapor barrier to reduce sink effects and infiltration/exfiltration. The existing poured-in-place concrete floor was used in both spaces. The ceiling was constructed of suspended 2' (0.55 m) by 4' (1.1 m) lay-in, acoustic tiles. Two standard 2' (0.55 m) by 4' (1.1 m) recessed fluorescent lighting fixtures were typically arranged in the ceiling, see Figure 2. The lighting

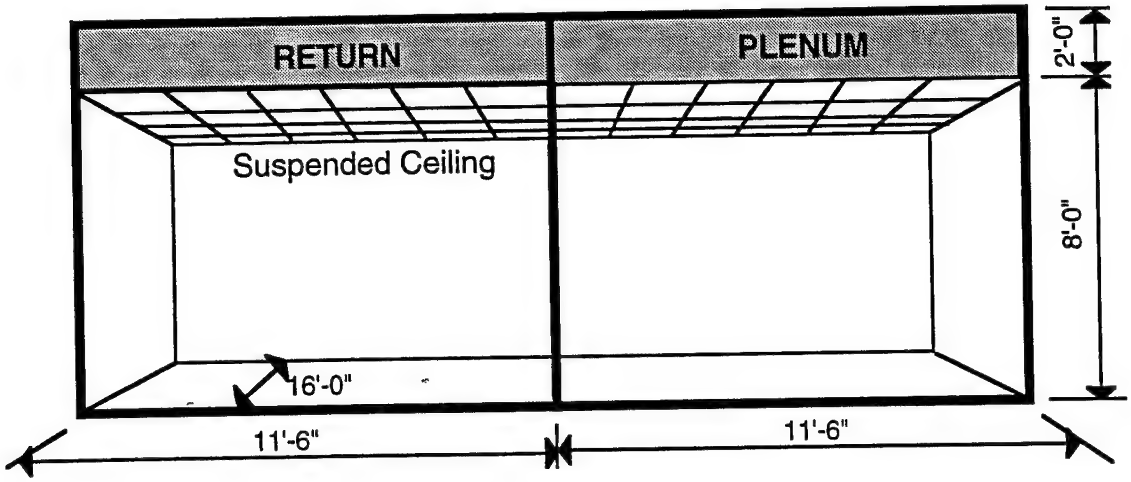

FIGURE 1. TEST CHAMBER PROPORTIONS

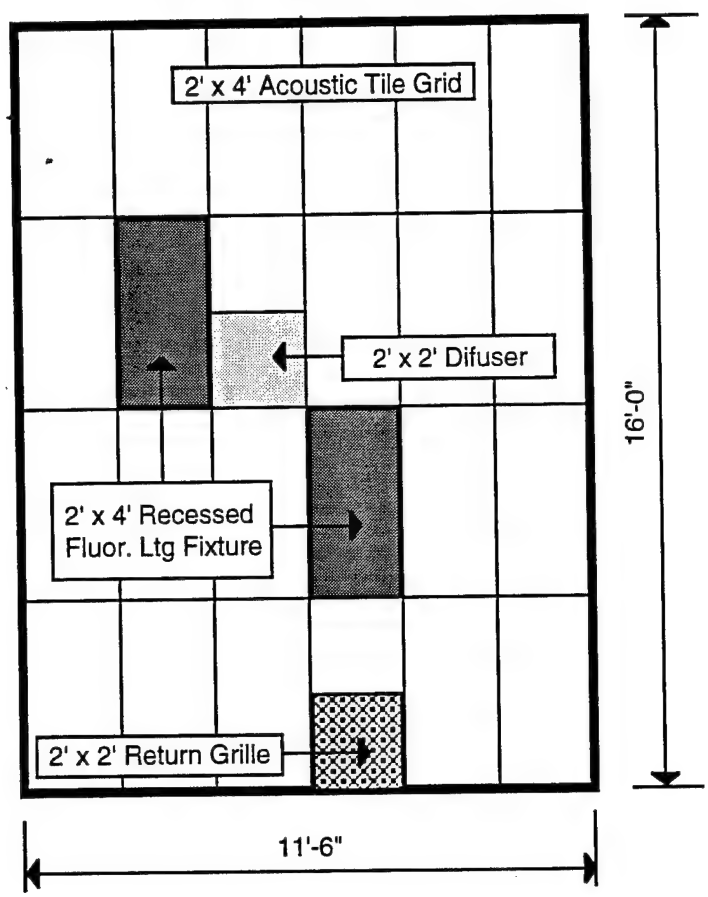

FIGURE 2. TEST CHAMBER REFLECTED CEILING PLAN.

system was wired to the lab's computer-based Energy Management System (EMS), and scheduled similar to the occupancy schedule.

Carbon dioxide is currently the most common pollutant source used for demand controlled ventilation. For a variety of reasons, using live subjects as CO_2 sources was not practical, therefore simulated occupants were used. For each space pure (99.999%) carbon dioxide was supplied at a rate representative of two adults (2x0.3L/m per person=0.6 L/m). The CO_2 was supplied from canisters through copper tubing to a hot water bath then to the test spaces. The temperature of the CO_2 was raised to approximately 95F before discharging to the space. This was believed to be the approximate temperature of an adult's exhaled breath. The CO_2 was dispersed through a spray nozzle mounted on an oscillator. The oscillator movement was representative of the head movement of an office worker. The nozzle was located near the center of the space at a height representative of the breathing level of a seated adult. The flow of CO_2 was controlled through two Mass Flow Sensors/Controllers, and the computer-based EMS system. The flow rate and on/off schedule of the CO_2 could be automatically controlled. Different schedules could be assigned to each space.

Another concern for the experimental setup was the impact on room air mixing from the thermal plume of the occupant. Therefore, in addition to the production of CO_2, the heat gain from the occupant was simulated. An electric resistance blanket was configured to represent a seated occupant and placed in each chamber. The temperature of the blanket was kept at approximately 85F which was believed to be an approximation for the average surface temperature for clothed and unclothed surfaces of a seated adult. The CO_2 nozzle and oscillator were located near the head position relative to the thermal blanket. The blanket provided a thermal plume similar to that of a live subject near the CO_2 dispersion point. The on/off schedule of the blanket was controlled through the EMS system and corresponded to the CO_2 supply schedule.

The test rooms were heated or cooled by a 500 cfm (236 L/s) fan-coil unit. Heating was provided by an electric resistance, duct-mounted heater. Cooling was provided by chilled water supplied by a packaged 3-ton chiller. The room air temperature was controlled by a standard wall-mount thermostat set for 75F. The air flow rate to each space was balanced and set at 210 cfm (99 L/s). This represented approximately 1.2 cfm (0.56 L/s) per square foot which was selected as the design air flow rate in a commercial office space. The air was discharged through a typical 2' (0.55 m) by 2' (0.55 m) ceiling mounted diffuser located near the center of the space. Air was returned either through a ceiling plenum or to the return duct through a grille located at the top of the wall with the door. This is a typical arrangement for enclosed offices. For tests performed for the plenum return the air was drawn out of the plenum from a single open-ended duct located between the two test rooms. For the ducted return arrangement separate returns were ducted to the ceiling return grilles for each space. Because only two rooms were studied it was expected that the test results for the plenum and common return duct locations would be similar. This will be discussed later.

To determine the controllability for different experimental conditions, thirteen CO_2 sensors were placed at selected locations throughout the occupied zone in each space. The experimental layout for the sensors are shown in Figure 3. The sensors were calibrated according to manufacturers recommended procedures and normalized according to the procedure developed by Meyers[5]. In addition to the in-room sensors, a sensor was located in the outdoor air intake.

For each test setup the flow of outdoor ventilation air was controlled through the EMS based on an average of two CO_2 readings from commercially available sensors. The average of these two sensors was used rather than a single controller to reduce concerns for the possible individualized characteristics of any one sensor. The flow of outdoor air was controlled from 0 to 100 percent of total flow based on the sensed level of CO_2. Outdoor air flow was measured using a cross-flow sensor and pressure differential transducer located in the outdoor air duct. The indoor CO_2 level was controlled between 600 and 1000 parts per million. For example, at an interior concentration of 600 ppm the outside air damper begins to open while at 1000 ppm the damper is fully open. The control logic utilizes a linear relationship between concentration and outdoor air damper position. While the 600 ppm is slightly lower than the control limit suggested by

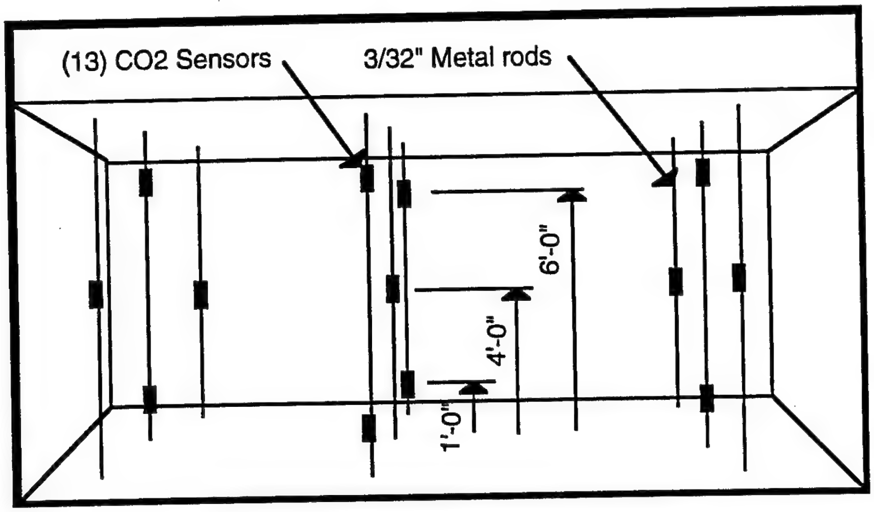

FIGURE 3. EXPERIMENTAL SETUP FOR CO_2 SENSORS.

Schultz[4], this value was selected to induce control action at the relatively low concentrations experienced for some of the experimental conditions.

Experiments were performed with the two control sensors located in-room, in a ceiling plenum, and in a common return duct. For tests performed at each location, different combinations of occupancy schedules were used in the test spaces. The flow of CO_2, lighting, and thermal blanket were turned on and off by the EMS system to represent different occupancy patterns between 30 and 100 percent occupancy. For example, 30 percent occupancy was represented by turning on the occupant simulator (CO_2 supply and thermal blanket) for 18 minutes of each hour and off 42 minutes, 50 percent occupancy would include 30 minutes on and 30 minutes off. Occupancies of 30, 50, 70, and 100 percent were simulated. Different combinations were used for each test space. For example, a 30-70 combination would be represented by 30 percent occupancy in the control space (in the case of the wall mounted, in-room sensor location), and 70 percent occupancy in the other "floating" space. Tests were run only for combinations where the "floating" space occupancy is greater than or equal to the sensor space. In this way the sensitivity of the room controllability to different occupancy patterns could be studied for the three sensor locations. Ten occupancy combinations were studied for each sensor location.

DATA ANALYSIS

Two hypotheses were proposed for this work:

1) The control sensor located in the common return duct would most closely approximate the average CO_2 concentration for both test rooms, and
2) Control of outdoor ventilation air based on the return duct sensor location would result in lower average in-room concentrations when compared to the other two sensor/controller locations.

To test these hypotheses the CO_2 concentrations were measured and recorded every two minutes throughout each six hour test period. Each test corresponded to a unique combination of control sensor location and occupancy schedules. For each test space the thirteen in-room CO_2 sensors were averaged into a single room concentration for each recording interval. A second average was calculated for both rooms using all 26 in-room sensors. This represented the average CO_2 concentration in both spaces ($CO2_{avg}$). Data were organized into three files, one for each control sensor location. Then the difference between the average concentration in both rooms and the average concentration of the two control sensors was calculated. Descriptive statistics for this

difference were compared as shown in Figure 4. As shown the results for the return duct location have the smallest difference between the control sensor and the average room concentration. This will be discussed later.

Descriptive Statistics — In-Room

	SENSOR DIFF
Mean	35.373
Std. Dev.	32.020
Std. Error	1.168
Count	752
Minimum	-52.602
Maximum	106.463
# Missing	0

Descriptive Statistics — Plenum

	SENSOR DIFF
Mean	13.577
Std. Dev.	18.912
Std. Error	.718
Count	694
Minimum	-37.880
Maximum	69.113
# Missing	0

Descriptive Statistics — RA Duct

	SENSOR DIFF
Mean	6.912
Std. Dev.	21.738
Std. Error	.794
Count	750
Minimum	-81.930
Maximum	73.388
# Missing	0

In-Room Plenum RA Duct

FIGURE 4. STATISTICAL COMPARISON OF AVERAGE ROOM CO_2 CONCENTRATIONS FOR DIFFERENT SENSOR LOCATIONS.

Next an analysis of variance was performed to test the hypothesis that the average room concentrations were lower with the common return duct location when compared to the other two locations. This was done by performing a multiple regression analysis using average room $CO2_{avg}$ concentration as a dependent variable and two of three bi-level (0 or 1) dummy variables that represent data taken at each sensor location (Room, Plenum, Duct) as independent variables. For example, if the data corresponded to tests performed for the in-room sensor/controller location then Room=1, Plenum=0, and Duct=0. For the plenum data, Room=0, Plenum=1, and Duct=0. This analysis can be expressed mathematically by equation 1. If β_1 and β_2 are statistically significant and positive this provides evidence in support of the hypothesis that the average room CO_2 concentrations increase when the sensor is located in-room or in the plenum. The results shown in Figure 5 indicate that the lowest average CO_2 concentrations ($CO2_{avg}$) are achieved with the Return Duct sensor/controller, this will be discussed later.

$$CO2_{avg} = \beta_0 + \beta_1 (\text{Plenum}) + \beta_2 (\text{Room}) \qquad \text{Eq.1}$$

Finally, it was thought that the controllability of the two test spaces might depend on the differences in occupancy (CO_2 emission) between the two rooms. Therefore, the effect of occupancy schedule on the average difference in CO_2 concentration for the two spaces was analyzed for the return duct location. Again multiple regression was used to estimate the effect of differences in occupancy schedule for the two test spaces. The dependent variable was the difference in average CO_2 concentration ($CO2_1$ - $CO2_2$)between the two test spaces. The independent variable was the difference in percent occupancy. For example, tests with one space occupied at 100 percent and the other at 30 percent would be represented by an independent variable level of 100-30 = 70. The analysis is expressed by equation 2 and results are shown in Figure 6. The magnitude of the β_1 coefficient represents the expected difference in average CO_2 concentration between the two spaces that results from differences in occupancy patterns between the spaces served.

$$CO2_1 - CO2_2 = \beta_0 + \beta_1 (\%OCC_1 - \%OCC_2) \qquad \text{Eq. 2}$$

Regression Summary
COMBINED AVG vs. 3 Independents

Count	2196
Num. Missing	0
R	.258
R Squared	.066
Adjusted R Squared	.065
RMS Residual	79.196

ANOVA Table
COMBINED AVG vs. 3 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	3	979290.613	326430.204	52.045	<.0001
Residual	2192	13748357.254	6272.061		
Total	2195	14727647.867			

Regression Coefficients
COMBINED AVG vs. 3 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	97.867	53.878	97.867	1.816	.0694
ROOM	25.636	4.091	.149	6.267	<.0001
PLENUM	6.762	4.202	.038	1.609	.1077
START	1.315	.123	.222	10.672	<.0001

FIGURE 5. ANALYSIS OF VARIANCE RESULTS FOR AVERAGE of CO_2 CONCENTRATIONS FOR DIFFERENT SENSOR LOCATIONS.

As shown in Figure 6 the difference in CO_2 concentration between the two test rooms increases as the difference in occupancy increases. This has potential consequences for controllability as will be discussed later.

RESULTS

The results from this study show that the first hypothesis seems to be correct and that for rooms operated with different occupancy patterns the control sensor located in the return air duct most closely approximates the average CO_2 concentration for both rooms, and that the in-room sensor experienced the largest mean difference with the average room concentration. This is supported by a comparison of the mean difference between the average concentration in both rooms ($CO2_{avg}$) and the average CO_2 concentration at the sensor/controller location. As indicated by Figure 4 the mean difference is much larger for the in-room location (35.373 ppm) as compared to the other two locations (Plenum = 13.577, Duct = 6.912). Not surprisingly, the results for the return air duct and plenum locations were similar although the lowest mean difference is shown for the return air duct location.

For the second hypothesis it was thought that for the test conditions studied the sensor/controller located in the common return duct would experience higher concentration levels

Regression Summary
ROOM DIFF vs. 2 Independents

Count	750
Num. Missing	0
R	.837
R Squared	.700
Adjusted R Squared	.700
RMS Residual	38.830

ANOVA Table
ROOM DIFF vs. 2 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	2	2633322.443	1316661.222	873.241	<.0001
Residual	747	1126316.610	1507.787		
Total	749	3759639.054			

Regression Coefficients
ROOM DIFF vs. 2 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	-1596.566	65.419	-1596.566	-24.405	<.0001
OCC DIFF	1.949	.078	.526	24.882	<.0001
START	3.612	.152	.503	23.757	<.0001

FIGURE 6. REGRESSION ANALYSIS RESULTS FOR AVERAGE DIFFERENCE FOR CO_2 AND PERCENTAGE DIFFERENCE IN ROOM OCCUPANCY.

when compared to the in-room sensor/controller and that these higher concentrations would result in the controller opening the outdoor air dampers sooner and thus providing lower average in-room concentrations. The higher concentrations in the return duct were anticipated because this location was thought to represent the average of the two spaces (one with high occupancy and the other low), while the in-room sensor/controller should more closely correspond to the occupancy pattern only for that particular space (low occupancy only). Since tests were performed for various combinations of occupancy schedules for the two rooms, differences in CO_2 emission rate existed. For the in-room sensor/controller tests, a worst-case approach was taken where the occupancy schedule in the space with the sensor/controller was always less than or equal to that of the other space. Therefore the average of the two rooms should be higher than in the space with the sensor/controller. Testing the reverse situation (sensor/controller in the space with high occupancy) was not thought to be necessary because outdoor air flow control based on the space with the highest concentrations would result in low CO_2 concentrations in all other spaces and consequently is not a condition of concern from an IAQ perspective. The consequences of this will be discussed later.

As previously discussed, the second hypothesis was tested by performing an analysis of variance using the average CO_2 concentration from both spaces ($CO2_{avg}$) as the dependent variable and two of three bi-level "dummy" variables (ROOM, PLENUM, DUCT) as the independent

variables. A third independent variable, START, represented the average CO_2 concentration at the start of each test and was used to factor out slight differences in the initial CO_2 levels for each test. The coefficients for ROOM and PLENUM shown in Figure 5 represent the average effect on room CO_2 concentration from locating the sensor/controller at each position as compared to the location not included as an independent variable (DUCT). Positive values for the coefficients indicate that as the sensor/controller is moved to each respective location the average room CO_2 concentration would be higher when compared to the return duct location. The highest coefficient is shown for the ROOM location (25.636 ppm) suggesting that on average the average CO_2 concentration will be 25.636 ppm higher when the sensor/controller is located in-room as compared to the return duct location. The t-Value suggests the statistical significance of the independent variable. Generally a t-Value greater than about 2.0 or less than -2.0 suggests significance. As shown the t-Value for ROOM is 6.267 indicating that the effect of the in-room sensor/controller location is statistically significant when compared to the return duct location.

The partial slope coefficient for the PLENUM is 6.762. This indicates that the average CO_2 concentration would be 6.762 ppm higher with the sensor/controller located in the plenum as compared to the return air duct. The t-Value is only 1.609. Because the t-Value is small this does not provide strong evidence that the effect of locating the sensor/controller in the plenum is statistically significant when compared to the return duct location. Therefore, the average in-room CO_2 concentrations were not significantly different for the plenum and the return duct locations.

A final analysis was performed for the return duct data to determine if there is a statistically significant effect on the difference in CO_2 concentrations between the two test spaces for differences in occupancy schedule. A regression analysis was performed using the difference in CO_2 concentration between the two rooms as the dependent variable and the difference in occupancy as the independent variable. As before the CO_2 concentration at the start of each test was also included to factor out slight differences in the initial concentrations. The analysis is expressed in equation 2. As shown in Figure 6 the average difference in CO_2 concentration between the two rooms increases as the percentage difference in occupancy increases. The magnitude of the partial slope coefficient shows that on average for every percentage point increase in the difference in percentage of maximum occupancy between the two rooms the difference in CO_2 concentration between the two rooms will increase by 1.949 parts per million. The t-Value (24.882) suggests that the effect is statistically significant.

DISCUSSION

There are several aspects of these results that warrant discussion. First, Figure 4 shows that the return duct sensor/controller location most closely approximates the mean concentration for both spaces and that the in-room sensor/controller experienced the most deviation from the average of both rooms. The plenum and return duct performed similarly. The similarity between the plenum and duct locations is further suggested by the results shown in Figure 5 where the t-Value for PLENUM is not statistically significant. This similarity results from the experimental setup where only two rooms were studied. For both the return duct and plenum locations the sensor/controller was located to respond to air from both spaces. In the return duct the air streams from both spaces are well mixed before reaching the sensor/controller location. Therefore, a well mixed average is created. For the plenum location the sensor/controller is located near the inlet of the return air in the plenum, near the center of the two rooms. In this case the average concentration for the two rooms is also approximated, and therefore both locations respond similarly. However, for larger spaces or for situations with more than two rooms are being served, plenum return air may be taken from several locations. Locating the sensor/controller near the inlet of any one of these plenum return locations could result in a bias reading as a result of local difference in concentration. While it is thought that for this situation the plenum location would more closely approximate the average concentration as compared to the in-room location, it may be less likely to perform as well as the return duct.

Another important consideration is that although the sensor/controller located in the return duct most closely approximates the average concentration for all rooms, it does not represent the concentration in any one space. This has potential consequences for sensor location selection and IAQ control in spaces where concentration differences exist between spaces. As shown in Figure 6 as the difference in occupancy pattern increases the difference in room CO_2 concentration increases and, therefore any one space may have high concentrations that are not detected when the air from several spaces is mixed, as in the return duct. This point can be made by considering the time-series plots in Figures 7 and 8 which compare the CO_2 concentration for the in-room and return duct locations to the average concentration in each space. Not surprisingly the in-room sensor tracks very well with the room in which it is located while the return duct is an average value not corresponding to either space. The greater the difference in CO_2 emission between the spaces the more likely that the return duct sensor/controller will not approximate any particular space. While this is less of a concern in spaces that have relatively similar occupancy patterns, when large variations exist this must be addressed.

RECOMMENDATIONS

If demand controlled ventilation is implemented using a single sensor/controller, the sensor should be located in the space that **always has the highest CO_2 concentration.** Unfortunately identifying this space may be difficult, in fact such a space may not exist. Most spaces experience temporal variations in occupancy. For any particular point in time a given space CO_2 concentration may be high or low relative to adjacent spaces. Therefore, selecting the "best" space to locate the sensor may not provide the desired control.

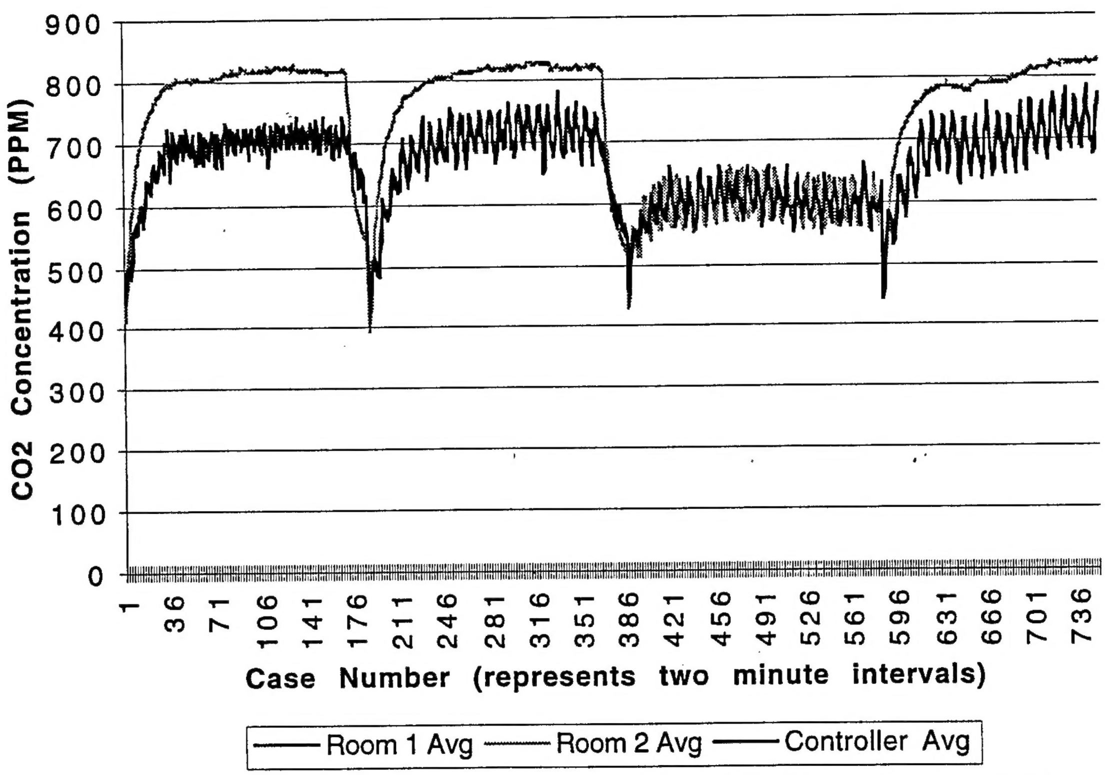

FIGURE 7. TIME-SERIES COMPARISON OF IN-ROOM SENSOR AND AVERAGE ROOM CO_2 CONCENTRATIONS.

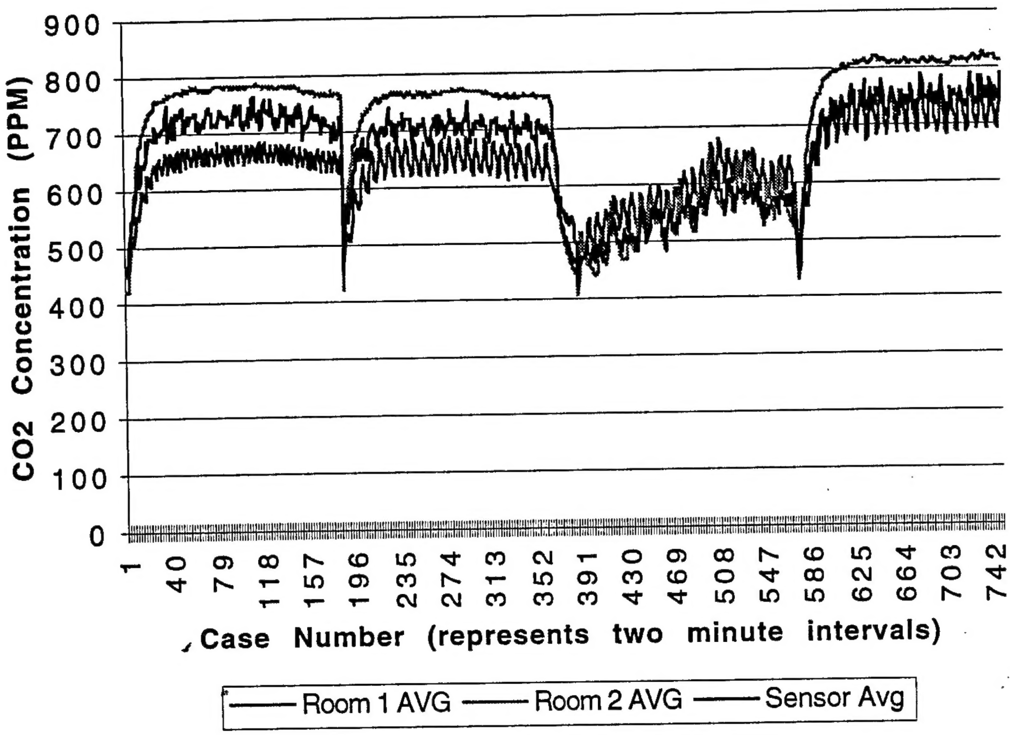

FIGURE 8. TIME-SERIES COMPARISON OF RETURN DUCT SENSOR AND AVERAGE ROOM CO_2 CONCENTRATIONS.

If a single sensor/controller is located in the return duct, the space to space variations must be recognized. When large differences in occupancy schedule exist the outdoor air flow control should include consideration for the differences between spaces and the average value being sensed. For example, an adjustment factor or offset should be added to the sensed value to account for the space with the largest concentration above the average. Determining the actual control logic may require some trial and error.

If demand controlled ventilation is to be applied for HVAC systems serving spaces with nearly identical characteristics and occupancy patterns, the placement of the sensor, either in-room, in the plenum, or common return duct will make little difference in the controllability of the CO_2 levels. However, for HVAC systems serving rooms with different occupancy patterns, such as offices and a conference room which may experience very high short-term CO_2 levels, a two (or more) sensor control arrangement is suggested where one sensor/controller is located in the return duct to maintain ambient levels and another located in the room expected to experience periodically high concentrations. For this arrangement a Discriminator Control arrangement would be used to compare the CO_2 levels from the two sensors, and control the outdoor air flow based on the higher value. When the conference room is occupied the in-room sensor would become the controller, and when the conference room is unoccupied the return duct sensor would control.

Ideally it would be best to have a CO_2 sensor in each space, compare the relative concentrations through a computer-based control system, and adjust the flow of outdoor ventilation air based on the "worst" case. In this way IAQ can be maintained with minimum energy consumption. The problem with this is first cost. At $400 to $1000 each for CO_2 sensors, locating a sensor in each space is cost prohibitive. As the cost for these sensors is lowered, the feasibility of this solution will become more attractive. Manufacturers are currently developing methods of reducing the cost of these sensors.

Finally, Demand Controlled Ventilation typically relies on CO_2 sensors. Obviously there are many other possible pollutants in buildings. Mike Schell [6] has suggested that a combined sensor strategy be employed using CO_2 and a broad-spectrum IAQ sensor. Some sensor manufacturers are currently developing combined sensors such as this. Although the cost issue will continue to be a concern in the near future, this combined sensor approach should be implemented.

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